THE NEW WORLD OF PHYSICAL DISCOVERY

FLOYD L. DARROW

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NEW WORLD OF PHYSICAL DISCOVERY

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A triumph of the new physics

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THE NEW WORLD OF PHYSICAL DISCOVERY

By

FLOYD L. DARROW

Author of

THE STORY OF CHEMISTRY, ETC.

ILLUSTRATED

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PREFACE

As its title indicates, this book portrays the ever-changing course of events in the world of physical discovery. After a brief initial survey of the sweeping changes which the discoveries of the last generation have necessitated in present-day view-points, the story paints the historic background of the picture. And although the progress of the centuries is unfolded in logical order, the panorama is everywhere viewed through the light of the new knowledge. That is the keynote of the book—the new concepts of the present epoch of exceptional achievement. While written in a thoroughly popular style, the treatment sacrifices nothing to scientific accuracy. The discussion, however, is entirely free from mathematical formulæ and those technicalities so forbidding to one not familiar with them. Its purpose is to acquaint the general reader with the salient features of the most fundamental of the sciences—a science which has exerted a tremendous influence in shaping the material and intellectual progress of mankind. One who follows the narrative from the beginning will travel the route that the pioneers of discovery blazed. He will see how knowledge grew, how each generation has stood on the shoulders of its predecessors—in short, how the edifice of modern physical discovery was built.

Throughout, the apparently irreconcilable conflict between much in the classical views and in those of the new world in which we find ourselves to-day has been emphasized. This is well illustrated in the chapter entitled "A Topsyturvy World," dealing with the new theories regarding the nature of energy and matter, the constitution of the atom and the transmission of radiation. Especially has Einstein's thought-provoking theory of relativity been presented in simple, understandable language. Admittedly abstruse, any difficulties which the reader may encounter are inherent in the subject itself. Yet, step by step, one is able to see how the theory originated and the basis for it. No one can come into even an approximate understanding of the contents of this chapter and not gain a broader and more comprehensive view of this vast universe of which he is a part.

So far as the author knows, this book gives for the first time a clear and comprehensive discussion in language that all may understand of the fascinating realm of physical discovery, more technically known as physics. It is believed that the reading of it will afford a liberal education in a subject which to many has been a sealed volume. This book does for physics what the author's *Story of Chemistry* does for a sister science. With the conviction that *The New World of Physical Discovery* meets a genuine need, it is offered to the reading public.

FLOYD L. DARROW

Brooklyn, New York.

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THE
NEW WORLD OF PHYSICAL DISCOVERY

CHAPTER I

A New Physical World

LAVOISIER AND THE LAW OF THE CONSERVATION OF MATTER—A FLOOD-TIDE OF NEW CONCEPTIONS—A NEW ERA—OLD IDEA OF MATTER DISAPPEARING—A REVOLUTION—VIEW OF PHYSICS AS A STATIC SCIENCE—PRINCIPLES REGARDED AS ESTABLISHED AT END OF NINETEENTH CENTURY—CONCEPTION OF FUTURE PROGRESS—SCOPE OF THE REVOLUTION—RELATIVITY—NATURAL ALCHEMY—A FINITE UNIVERSE—COSMIC RAYS—PRINCIPLE OF ENTROPY—MECHANISTIC UNIVERSE VANISHES—MAN AT THE BEGINNING OF HIS EXISTENCE—OUR SOLAR SYSTEM AND THE HUMAN RACE POSSIBLY UNIQUE—FORECAST OF FUTURE PAGES.

Before me lies a portrait of Lavoisier, great French savant who lost his head in the Revolution because its leaders had "no use for scientists." First correct interpreter of the fundamental chemical process of combustion, this gifted Frenchman, whose only passion was the pursuit of truth, is remembered to-day equally well for his work in laying the foundation of the Law of the Conservation of Matter, one of the corner-stones of nineteenth-century physics.

A century and a quarter have slipped by since the tragedy of his taking off, and we find ourselves in a new physical world. The fancied security of centuries, almost overnight, has been swept aside. Had Lavoisier returned to earth only a generation ago, he would have found himself at home. True, he would have discovered a wealth of scientific progress, but nothing that could be termed "revolutionary." Then, with a suddenness that was startling, came a veritable flood-tide of new conceptions. Experimental fact and theory, upsetting, even bewildering, to time-honored ideas, have precipitated us headlong into what is often called the "new physics." The boasted permanence of the nineteenth-century edifice has disappeared. Its once substantial foundations are swaying. Discoveries, incredible to the classical thought of Faraday, Maxwell and Kelvin, are being marshaled under the banners of Planck, Einstein and Millikan. And the marching song of the new era is set to the music of *The World's Upside Down.*

Should you ask a high-school student of physics to-day about Lavoisier's principle of the conservation of matter, he would tell you that, while this law still holds for all practical purposes, its earlier prestige has disappeared. The old idea of matter as something solid, hard, tangible and indestructible as such has gone. The rock-ribbed hills, the ocean deeps, the atmosphere, we ourselves and all that we may see have been resolved into moving points of electric energy, or what seems more than likely just now into bundles of energy waves. Matter and energy have become separate aspects of one fundamental reality. Each is convertible into the other. The solid masses of the stars are dissolving to keep alive the celestial fires. All is flux. The inviolability of matter has disappeared.

In a multitude of ways the physical world of yesterday is upside down. Without exaggeration, we may term this upheaval a revolution. Just at the close of the last century, the foremost leaders in this realm of thought viewed physics as a static science. All the fundamental principles had been discovered. The seventeenth and eighteenth centuries had seen the triumph of the laws of mechanics; Huyghens had put forth his epoch-making wave theory of light, and it had received wonderful confirmation from the researches of Young and Fresnel in the first half of the nineteenth century; the work of these investigators and others, too, had established on a seemingly secure basis the beautiful conception of the all-pervading ether of space; the far-reaching principle of the conservation of energy had evolved from a scientific dream to actuality; the conception of the dissipation of energy, known as the Second Law of Thermodynamics and also as the principle of entropy, was believed to be beyond attack; working from the experimental data provided by Faraday, Maxwell had developed the electromagnetic theory of light, unifying the phenomena of electricity and light, and Hertz had supplied its experimental verification.

A tidy world this was, and well might the recipients of so priceless a heritage view it with pride. Their only task was to keep the estate intact, tend the vineyard and enjoy the well-earned fruit of previous centuries of labor. No new varieties were expected to blossom forth on the tree of physical knowledge. Future progress would consist only in a little more intensive application of well-known methods and principles.

Then, lo, the revolution. While these learned savants were viewing with smug complacency their rich inheritance and were delivering addresses of congratulation that in one important field of science investigators were nearing the end of the journey, the first X-ray photographs were published. Before the world had caught its breath from this announcement, radio began its matchless conquest of space, with the unfolding of a whole new realm for physical research. The Curies discovered radium and the phenomena of radioactivity, giving for the first time that marvelous peep within the atom which has revolutionized our conceptions of the structure of matter and the sources of radiant energy. On the border-line between the old century and the new, Planck announced his theory of the granular structure of energy and thus opened up a field of inquiry which we have hardly yet begun to explore. This quantum hypothesis of Planck has already compromised the "impregnable" position of the wave theory of light and has brought a return, for certain manifestations of Nature, to something resembling the abandoned corpuscular theory of Newton. A first-class dilemma had been created, the way of escape from which is not yet clear. But the waters had only begun to be troubled. The worst was yet to come.

A dozen years before, Michelson and Morley had performed that now world-renowned experiment which for the first time cast doubts upon the existence of the ether and indicated the impossibility of ever being able to discover any such thing as absolute motion. In a word, it ushered in the vogue of relativity, a conception of the universe which has shaken the physical world to its very foundations and with the bewildering perplexities of which we are still struggling. Space, time and gravitation have assumed new and wonderful meanings—unpicturable, repugnant to common sense, and yet undoubtedly true.

Before two decades of the present century had passed, Rutherford was battering the atoms of certain elements to pieces and thereby producing lighter elements from heavier ones. Thus, the dream of the alchemist had come to pass, albeit not in the way he anticipated. Furthermore, from this new experimental knowledge of swiftly moving subatomic units, Einstein has been able to show that mass is a property of velocity and that matter and energy, as already stated, are equivalent, the transformation being strictly in accord with a precise mathematical equation. Light, too, has been made subject to the sway of gravitation. All of which was as foreign to the thought of a nineteenth-century physicist as the meanings of the stars were to the caveman.

The "starry heavens," which so awed Kant, have been transformed. It is no longer good form to speak of the "infinite depths of space." If the principle of relativity is valid, our universe is finite, not infinite. How this may be, we shall see later. According to Millikan, too, the cosmic rays indicate that elements in the utmost profusion are continually being born in inter-stellar space. The radiant energy of the stars is being converted into the primordial stuff from which nebulæ, suns and solar systems arise. Perhaps the principle of entropy, or the degradation of energy, regarded as a corner-stone of nineteenth-century discoveries in physics, is not everywhere and always true. The drama of perpetual change going on within these cosmic crucibles constantly becomes more clear. The evolution of a star is no longer a mystery. It is known, too, that densities as great as a ton to the cubic inch, sixty thousand times as great as the density of water, exist in certain stars. It requires no stretch of the imagination to understand that in such unique niches of the universe physical conditions and forces prevail, altogether at variance with those encountered in terrestrial laboratories. A nineteenth-century physicist would scarcely find himself at home in a laboratory on, say, the companion of Sirius.

The eighteenth-century idea of a mechanistic universe has vanished. That all natural phenomena can be explained in terms of mechanical forces is an unrealized dream. The fascinating pastime of trying to invent model machines to account for every natural process has passed. For instance, we can form no picture of a mechanism for the transmission of radiant energy. Human ingenuity has not proved sufficient to reduce this universe to the product of a rigid mold. From farthest sun to farthest sun, it is vibrant with energy in its manifold manifestations. But mechanics alone does not afford the key to its understanding.

Here we are, children of the universe, adrift upon this bit of earth and sea and sky in a vast ocean of time and space, and yet the possibility of all knowledge may lie within our ken. But we do well, as Jeans admonishes us, to reflect "that mankind is at the very beginning of its existence; on the astronomical time-scale it has lived only a few brief minutes, and has only just begun to notice the cosmos outside itself. It is hardly likely to interpret its surroundings aright in the first few moments its eyes are open."

Jeans tells us, too, that our solar system is more than likely a freak system, something unique in the universe. There may not be more than one other like it in a cosmic space which numbers possibly thirty billion suns. Not more than once in ten million million years could the chance meeting of two suns, whose enormous tides give rise to such a system, take place. And it may be that in the stupendous sweep of uncounted ages the human race is but a passing incident in the process of cosmic evolution—in terms of biology a cosmic mutation. Still, it seems to be given to its members to unravel some of the mysteries of this universe of space, time and energy. But the physical world of to-day differs from that of yesterday, just as it in turn will be broadened by growing into that of to-morrow.

In the following pages, we shall unfold something of the evolution of our constantly growing knowledge of the physical world as it has developed from early conceptions to its present outlook. We shall tell the story of the past, but most of all we shall take excursions into the fascinatingly new realm of twentieth-century physics. And we shall view it all in the light of the new discoveries.

CHAPTER II

FROM EARLIEST DISCOVERER TO NEWTON

THE FIRST PHYSICIST—CONTACT WITH THE FORCE OF GRAVITY—EARLY MECHANICAL DEVICES—WORKS OF THE EGYPTIANS—PROGRESS IN ENGINEERING—CONTRIBUTIONS OF BABYLONIANS—POVERTY OF GREEK GENIUS IN REALM OF PHYSICS—ARISTOTLE—EXCEPTIONAL RECORD OF ARCHIMEDES—OTHER GREEK SCIENTISTS—ROGER BACON—EPOCH OF GALILEO—LEONARDO DA VINCI—REFUTING ARISTOTLE'S DICTUM REGARDING FALLING BODIES—COPERNICUS AND HIS NEW CONCEPTION OF THE HEAVENS—BRAHE AND KEPLER—KEPLER'S LAWS—GALILEO DEFENDS THE COPERNICAN VIEW—GALILEO AND THE TELESCOPE—THE PENDULUM—MEANING OF MOMENTUM—THE LAW OF INERTIA—ILLUSTRATIONS—LAWS OF FALLING BODIES—MEANING OF ACCELERATION—PATH OF A PROJECTILE—DEFINITION OF FORCE.

WHO the earliest physicist was, no record discloses. Certain it is, however, that primitive man had scarcely taken a step on his long march from the jungle toward civilization until he began, unwittingly though it be, to acquire a mastery of those physical laws and forces which has enabled his successors to dominate the earth. From his earliest years, he must have observed the movements of the sun, moon and stars. Still, little did he suspect that in the slow acquisition of knowledge regarding those vast starry spaces, so awe-inspiring and mysterious, some of the noblest monuments in the growth of physical science were to be erected. Sometime, somewhere he gained the mastery of fire and thence by easy stages, slowly, blunderingly, came into possession of the simpler arts of metallurgy. His every movement was conditioned by the influence of the stubborn force of gravity. Against it, he was forever compelled to pit his puny strength and his prowess. The very weight of his own body was often an obstacle. Occasionally, as when he may have hurled rocks from some projecting cliff upon wild beasts below, he was able to make this apparently natural foe serve his simple needs. In all the early works of building a civilization, he had to overcome it, and in so doing, step by step, he acquired a knowledge of the fundamental principles of the simple machines. Without knowing it, he was laying the foundations of the modern science of physics.

It is said that Aristotle was acquainted with "the lever and balance-weight, the beam scale, tongs, wedges, crank and axle, roller, wheel and pulley, pulley block, potter's wheel, catapult and toothed wheel." This represents the heritage from antiquity, the slowly accumulating fund of a science of mechanics, resulting from many millennia of rule-of-thumb practise. The prehistoric hunters had fashioned the club, spear, ax, knife, and bow and arrow. The earliest tillers of the soil employed the plow, spade and sickle. When metals became available, craftsmen devised crude saws, shears, the gimlet, plane, tongs, lathe, bellows, loom and potters' wheel. The wheel, first as a mere roller and afterward fitted with a fixed axle, may have been the first real machine. As early as 3000 B. C., there was invented in Egypt a machine employing the principles of the screw and the lever.

Indeed, it was those dwellers by the ancient Nile who initiated the science of engineering, which is simply applied physics. Their dikes and canals, their colossal temples of polished granite, noble in design and beautiful in architecture, and their tombs and great public edifices, worthy of the highest civilizations of later times, are eloquent memorials to a genius for applied science unsurpassed by any other people of antiquity.

What marvelous engineers the builders of the pyramids were! To this day, it is unknown exactly how these mighty monuments were erected. For lack of any comprehensive familiarity with the principles of mechanics, they speak of the infinitude of human toil. In their construction, life was counted as dust in the balance. By some unknown combination of levers and planes, one hundred thousand men through a period of twenty years lifted the mammoth blocks of the Great Pyramid into position. A single stone in the Colossus of Rameses II has been found weighing twelve hundred tons. It is believed that, with weighted levers placed on either side of a huge stone, it was lifted a short distance and held suspended while armies of workmen under the lash of the whip master filled the space beneath with earth. Then the process was repeated again and again until the requisite height was reached, after which the stone was allowed to slide down a prepared incline into position. What this meant can be gathered from the fact that the Great Pyramid stands four hundred and fifty feet above the Nile.

The Egyptians and also the Mesopotamians were early masters of hydraulic engineering. Their civilizations were intimately related to the river systems of the Nile, the Tigris and Euphrates. Irrigation was a necessary art. From vernal equinox to summer solstice, it is estimated that each acre of the valley of the Nile required sixteen hundred tons of water to insure its fertility. By means of a weighted beam and a bucket, the water was lifted distances ranging from eighteen inches to thirty feet, being poured into a receiving basin. As eight feet was the maximum distance possible to lift water with this device, it was frequently necessary to repeat the operation several times. The first harnessing of water to the performance of useful work may have been an undershot water-wheel, with buckets on the circumference, which the Egyptians learned to install, where the current was swift enough, for automatically lifting the water and discharging it into a trough.

About 300 B. C., the screw as a working machine originated in Egypt. Thus, before the beginning of the present era each of the six fundamental machines was in practical use. However, a knowledge of their principles and an actual science of mechanics were yet to come.

OUR DEBT TO THE BABYLONIANS

Every high-school student of physics knows that exact measurement is a distinguishing feature of laboratory methods. He probably seldom stops to think, however, that many of the units of these measurements are hoary with age. To the Babylonians we are indebted for a week of seven days and a day of twenty-four hours. They, too, divided the hour into sixty minutes and the minute into sixty seconds. Whether we agree with Einstein in the relativity of time or accept the view of Newton, the humblest industrial worker and the most learned scientist measures the hours of his labor or the periods of his observations in accordance with a time scale established by Babylonian physicists possibly five thousand years ago. Engineers and astronomers of to-day, too, reckon angles in degrees, minutes and seconds, as did the self-made scientists of Mesopotamia at the dawn of history. As early as 343 B. C., Cidenas, a Babylonian astronomer beside the Euphrates, discovered the slow precessional movement of the equinoxes, a quantity amounting to only one and two-tenths degrees per century. Here was an achievement of which a modern scientist might well be proud. And these Babylonian pioneers invented sun-dials and water-clocks, and introduced the beam balance for weighing medicines and valued treasures.

GREEK GENIUS IN THE REALM OF PHYSICS

Brilliant as were the accomplishments of the Greek genius in the fields of mathematics, logic, metaphysics, literature and art, there is little to their credit in physical science. If you were to search your memory of Greek history for an important discovery by a Greek physicist, aside from the work of Archimedes, not much would be disclosed.

Of course we recall that Thales of Miletus, one of the "seven wise men," is credited with the prediction of an eclipse in the sixth century B. C. and with a knowledge of the electrical properties of amber. Pythagoras, contemporary with his later years, is said to have been the first to advocate that the earth is a sphere. Tradition, too, tells us that Pythagoras discovered the intervals of the musical notes. From his speculations came also the beautiful conception of the "harmony of the spheres."

However, we usually think of Aristotle, teacher of Alexander the Great and uncrowned czar of science for nearly two thousand years, as the outstanding Greek leader in this field. Nevertheless, his influence was a pernicious one. We remember him chiefly as the perpetrator of one of the most colossal blunders in the whole history of science. Because it seemed plausible to his unscientific sense of the eternal fitness of things, this Greek speculator unhesitatingly gave the weight of his immense influence to the false assumption that a body weighing one hundred pounds will fall under the spell of gravity one hundred times as fast as a body weighing one pound. Not until the famous experiment of Galileo at the Leaning Tower of Pisa in the sixteenth century was the ghost of this myth finally laid. Aristotle, too, was the author of the celebrated statement that "Nature abhors a vacuum." Not until many centuries later when it was discovered that "evidently Nature's abhorrence of a vacuum does not extend above thirty-four feet" in pumping water at sea-level, did a glimmering of the real explanation of this fact of physics enter men's minds.

The Greeks did a prodigious amount of philosophizing but performed very few experiments. As an illustration of their fallacious methods of reasoning, we may take Aristotle's proof that the world is perfect. He said, "The bodies of which the world is composed are solids, and therefore have three dimensions. Now, three is the most perfect number—it is the first of the numbers, for of *one* we do not speak as a number, for *two* we say both, but *three* is the first number of which we say *all.* Moreover, it has a beginning, a middle, and an end." Little wonder that the Greek genius made so few discoveries in physical science. Great as these men were, they simply did not have the bent for scientific investigation.

Every reader of this book who once studied high-school physics is acquainted with *Archimedes' Principle.* More than likely he can tell the story associated with its discovery. He knows that King Hiero, of Syracuse, the native city of Archimedes, called upon this most distinguished scientist of antiquity to determine whether the goldsmith who made his crown had alloyed it with the baser metal silver.

Likewise, he knows that the solution of the problem led to the discovery of the relationship existing between the weight of a body in air and the weight of liquid it displaces, either for a sinking body or one that floats. Thus the laws of buoyancy became as an open book, and a beginning was made in an exact understanding of the physics of liquids. This, too, marks the first instance of the definite formulation of a law of physics. It is the only principle coming down from antiquity which we include in our textbooks to-day.

Many stories are told of the scientific prowess of Archimedes. He invented a screw for lifting water and powerful machines for hurling missiles against the enemy. He is credited with an ingenious arrangement of burning glasses for setting fire to the Roman ships in the harbor. As a mathematician, he had no superior in his time. The well-known statement, "If I had a lever long enough and a place to stand, I could move the earth," shows that this gifted Greek had some knowledge of the simple machines. He deliberately practised the experimental method. Although he lived in the third century B. C., he was the first of modern physicists. His untimely death at the hands of a Roman soldier, while deeply absorbed in the solution of a mathematical problem, is the first recorded tragedy in the history of science.

Two other Greek scientists, we must mention before passing on to the beginnings of modern physics in the Middle Ages. Both were contemporaries of Archimedes. Eratosthenes calculated the circumference of the earth, placing it at two hundred and fifty thousand stadia, and Aristarchus, the "Copernicus of Antiquity," proposed a theory of the solar system practically identical with that of to-day. Although his figures were inaccurate, Aristarchus computed the relative sizes of the sun, earth and moon and their distances from one another. For the first time in history, and at a comparatively early time too, he pointed out the absurdity of assuming that the sun revolves about the earth and traverses such an immense orbit each twenty-four hours. Unfortunately, Hipparchus, his successor, did not accept this advanced view, and the world was compelled to wait two thousand years for its confirmation.

Greek science failed because it was based upon speculation rather than upon experiment. Since the time of Galileo, no scientist has been able to obtain a hearing who did not advance tested truth in support of his claims. However, as in the case of Einstein, this tested truth has not always been in the nature of direct experiment. Physics is preeminently a mathematical science, and often theories of the utmost significance arise from this precise method of treatment, theories which later find their confirmation in the laboratory. As we shall see, Maxwell's development of the electromagnetic theory of light is a case in point. Every such theoretical advance has had its origin in the experimental researches of earlier workers. Armed with the mathematical method and supported by experimental research, the modern physicist for more than three centuries has been a mighty discoverer of fundamental truth. The Greeks failed because they had neither the inclination nor the aptitude for this method of approach. A capital example occurs in the contrast between the purely speculative atomic theory of Democritus and the experimental one of John Dalton.

THE HERALD OF A NEW ERA

In Roger Bacon, whose genius "was crushed by the political and mental despotism of his time," we find the forerunner of a new era in physical science. Born in the thirteenth century of an ancient family of wealth and distinction, Bacon was one of the most gifted men of the Middle Ages. He was educated at Oxford and Paris and later became famous as a professor at the former institution. That he might know all that had been written upon scientific subjects, he mastered the Greek language and secured the best texts available.

During a period of twenty years at Oxford, Bacon spent no less than two thousand pounds for instruments and apparatus with which to carry on experimental work. That is why he is called the herald of a new era. He saw the utter futility of the Greek method. With an insight worthy of a present-day worker, he sensed the necessity for direct investigations. However, he was several centuries in advance of his time. As is well known, he spent many years in prison in punishment for his "heresies."

The actual experiments of this pioneer of the new order are of little moment. That he was an earnest alchemist there is no doubt. Alchemy was an important business in those days. His writings show that he was familiar with gunpowder and its properties, whether, as is often asserted, he was the discoverer of it or not. He experimented in optics and was acquainted with the properties of lenses and spherical mirrors. The refraction of light came under his observation, and he discussed the reasons for the enlarged appearance of the sun and moon when near the horizon. Although the magnifying power of lenses was known to him, there is little ground for believing that he invented a telescope.

It was intellectual inertia that frustrated the work of Bacon. Inertia is a term big with meaning in the realm of physics. It is one of the most fundamental properties of matter. It, of course, means inactivity—the universal tendency, whether in the world of physical things or in that of mental phenomena, "to stay put." Men do not like to be jostled from their comfortable niches of mental security. The men of Bacon's day had allowed ideas inherited from an age of imperfect knowledge to gain a steel-trap grip on their intellectual processes. They faced the past and not the future. This barrier was too strong for him single handed to break down. But across the centuries that have since gone the example that he set stands forth like a great mountain peak in a lonely desert.

THE EPOCH OF GALILEO

We say the epoch of Galileo because this gifted researcher of Pisa, Florence and Padua was the dominating personality in the awakening of science which followed the Italian Renaissance. Preceding him, however, by a century was that many-sided genius of medieval art, Leonardo da Vinci. He was the most scientific artist that ever put brush to canvas or designed a work of architecture. That he was a scientist of wonderful insight and prophetic vision, the record of history leaves no room for doubt. He anticipated Copernicus in setting forth the movement of the earth; he invented a device for measuring the traction power of machines; he is credited with the discovery of the camera obscura; he studied fossils and came to correct conclusions as to their geologic history; he designed flying machines of the airplane type. However, like Bacon, he was too early. The waters of an age of intrenched ignorance and intellectual inertia engulfed him. We honor him to-day as the brilliant prophet of modern ideas and methods in physical science.

Let us now return to Galileo. From him we date the beginning of a continuous science of practical physics. He is the first original investigator who made so profound an impression upon his age that he simply could not be forgotten by his immediate successors. His works lived after him in a most vital way. They formed a nucleus which with the passing of the years grew into a vast body of accumulated fact and theory. He hit the fallacies of ancient myth and error, and he hit them hard, so hard that his enemies could not forgive him, and thereby unwittingly they bequeathed his discoveries as a priceless heritage to posterity. With a breadth of vision unsurpassed elsewhere in the whole history of science, Galileo grasped in its full significance the importance of experimental research. Thus he became a master no less great than his distinguished contemporaries in the field of art.

The experiment from the top of the Leaning Tower of Pisa has already been mentioned. There, as all the world knows, Galileo put to practical test Aristotle's dictum regarding falling bodies. But the worshipers of the past would not be convinced. Angered by this audacious assault upon the citadel of ancient error, they rushed home to look up the very page and line where the Greek father of all scientific truth had announced as a matter of pure speculation a contrary result. Being human, puffed with pride and conceit, jealous of their inherited opinions and utterly incapable of any appreciation of the crucial importance of actual experiment, these quite natural bigots of their day came to hate Galileo. He spoke a language which they could not and would not understand. Students and professors at the University of Pisa, where he held the chair of mathematics, hissed him and accused him of being a magician. So unpopular did he become that he fled to Padua, where friends had secured for him a professorship in the university.

To get the setting for the next chapter in the career of this Italian physicist, we must hark back to three men whose discoveries paved the way to the first great scientific revolution in human history. The first of these was Nicolas Copernicus. The mere mention of his name is almost sufficient. But let us emphasize that he did not base his theory upon other men's views. A mathematician by education and a churchman by profession, he was a clear and independent thinker. The clumsy astronomical system of Ptolemy, with its theory of epicycles for explaining the irregular movements of the planets, did not seem plausible to this "silent watcher of the night." In particular, he studied the varying brightness of the planet Mars and became convinced that the ancient theory did not sufficiently account for what he observed. He wondered if there were not some other explanation. Going back to the literature of the Greeks, he found that Pythagoras and others had advanced a theory of a solar system with the sun at its center. Copernicus revived this Greek conception. But he did more. Through his own observations, he produced a mass of evidence in support of his conviction overwhelming in its significance. Therein he differed from nearly all his predecessors and contemporaries and displayed the spirit of a modern physicist.

As is well known, Copernicus feared to publish the monumental treatise setting forth his revolutionary view of the heavens. For thirty years he kept it in manuscript form, discussing its contents only with his friends. Not until he was on his death-bed, in 1543, was a copy of the printed volume placed in his hands.

The Copernican view of the heavens seems simplicity itself to us in this first half of the twentieth century. We have been brought up on it. And yet there was a time in the childhood of each of us when the idea that there were people on the other side of the earth walking with their heads down seemed absurd and utterly opposed to common sense. If we wish to appreciate the feeling of people in those times with reference to the new universe created by Copernicus, all we need to do is to consider our own reaction to some of the paradoxes of Einstein's theory of relativity. Are the ideas of curved space and a finite universe any less repugnant to common sense than were the sixteenth-century notions of a spherical earth rotating on its axis and revolving about the sun? We have grown accustomed to the Copernican view.

It no longer seems absurd. We know that it is true. A wealth of observation and demonstration tells us so. When Magellan, for instance, crossed the seven seas and circumnavigated the globe, no one could longer doubt the sphericity of the earth. Likewise, we shall some time come to accept the Einstein view. To a generation that has been taught its fundamental principles, there will be little that is paradoxical about it. Familiarity will disarm opposition.

The second and third of these men who set the stage for some of Galileo's most notable discoveries were Tycho Brahe and Johann Kepler. One can not be mentioned without the other. Working from the data left by Brahe, Kepler made the first discoveries of precise astronomical laws in human history. More than this, he provided the basis upon which Newton was to build his conception of universal gravitation.

Tycho Brahe, who lived during the second half of the sixteenth century, was the world's first professional astronomer. At Uranienborg in Denmark, he built the first observatory. For more than twenty years he studied the heavens, collecting a great mass of original observations on the sun, moon, planets, comets and stars. With infinite pains and labor, he determined the positions of seven hundred and seventy-seven fixed stars. When we recall that this was all done without the aid of the telescope, which was not invented for a decade after his death, what he accomplished seems all the more prodigious. His picture of the heavens was a cross between that of Ptolemy and the system of Copernicus, but he did not believe in theorizing. He was an accumulator of facts, and it is upon facts that science builds.

Kepler, beset throughout his troubled life by poverty, ill health and misfortune, formulated three laws of planetary motion which for the first time gave a true picture of our solar system. As assistant to Brahe, he inherited the wealth of astronomical data obtained by the great Danish observer. To these he brought his genius as a mathematician and continued the observations after his master's death. Out of this work grew his famous trio of laws.

Kepler began his work with the assumption that the orbit of each planet is a circle. The circle had, since the time of Aristotle, been regarded as the perfect curve. However, his observations of the planet Mars soon convinced him that, if its orbit were a circle, the sun was not at the center of it. Then he noticed that, when Mars was nearest to the sun, its motion was more rapid than when it was farther away. This discovery led Kepler to the idea of an elliptical orbit with the sun at one of the foci. Applying his knowledge of geometry, he found that this sort of a curve would fit the facts of observation, both theoretically and practically. Not only did it work for Mars, but for the other known planets as well. Accordingly, Kepler announced this fact as his first law, namely, that the path of each planet about the sun is an ellipse with the sun at one of the foci.

From the very first Kepler had been possessed with the idea that in the motion of a planet a line joining the planet with the sun, known as the radius vector, must sweep out equal areas in equal times. He now proved that this is true. Thus his second law took its place in the scheme of solar order. Why this should be so, however, he did not know. It was a profound puzzle. Kepler had no conception of a law of gravitation. The inertia of a moving body had not crossed his mental horizon. Curious as it now seems, he imagined some sort of a pushing force, tangent to the orbit and shoving the planet along from behind. That is, the work of Kepler was wholly empirical. He did not arrive at any working theory of fundamental aspects. I hesitate to say *causes,* for the idea of ultimate cause is not now in good form.

Still, Kepler did not feel that his work was complete. He had an intuitive feeling that some mathematical relationship existed between the average distances of the different planets from the sun and the times of their revolutions. It is a part of the genius of this man that he should have had such an intuition. For years he strove for a solution of this problem. At length he found it. It constitutes his third law and is stated thus: *"The squares of the times of revolution of the planets are proportional to the cubes of their average distances from the sun."*

Although this statement seems perfectly clear, let me illustrate it with reference to Mars and the Earth. If we divide the square of the period of Mars' revolution by the square of the Earth's period, the quotient obtained will be precisely the same as that found by dividing the cube of Mars' average distance from the sun by the cube of the Earth's average distance.

For the first time in the vast amount of theorizing in which men had indulged, definite, concrete evidence was produced to show, as one astronomer has put it, that "the heavens are crystallized mathematics." It is the beauty of physical laws that they are susceptible of this interpretation. Without this fact, the universe would be chaos and not a cosmos. It will be to the everlasting credit of Johann Kepler that he was a pioneer in establishing this conception.

Kepler died just three hundred years ago (1630). The following extract from one of his books is as sound doctrine to-day as it was then: "If any one be too dull to comprehend the science of astronomy, or too foolish to believe in Copernicus without prejudice to his piety, my advice to him is, that he should quit the astronomical school, and condemning, if he will, any or all the theories of philosophers, look to his own affairs, and leaving this worldly travail, go home and plough his fields."

Now let us return to Galileo, the firebrand of the new order. He had been six years at Padua, and the Senate had renewed his appointment for a second term of equal length at a greatly increased salary. His brilliance as a teacher, his ready wit, his command of language and his keen and original mind made him the ornament of the university faculty. Secretly he was in full sympathy with the Copernican theory, which was then more than half a century old. However, knowing the spirit of the times and remembering his experience at Pisa, he hesitated to announce his views. Still, he could not long contain himself. A new star blazed forth in the heavens, and Galileo gave three public lectures upon this astronomical event to large audiences. In them he took occasion to emphasize the upset which this phenomenon of the skies gave to the ages-old Aristotelian doctrine of the immutability of the heavens. His faculty associates were annoyed at the appearance of the star, but more so because of Galileo's bold discourses on it. With this he threw restraint to the winds. Abandoning caution, he accepted the challenge. Thenceforth he became an eloquent defender of the "faith." By analogy, experiment and wit, he proclaimed the new ideas to the populace in the vernacular of the day. Once more the conservatism of two thousand years found itself baffled by the new spirit of scientific inquiry and attacked by weapons which it did not know how to use.

Just at that time news came to Italy of the invention of the telescope by a Dutch optician, Hans Lippershey. Eagerly Galileo seized upon it. Here might be an instrument with which he could refute his enemies and demonstrate the correctness of his views. All night he sat up trying out combination after combination of lenses. By morning he had a telescope—an old organ pipe with a lens thrust into either end—which magnified three times. Away he rushed to show it to his friends. He says, "Many noblemen and senators, though of advanced age, mounted to the top of one of the highest towers to watch the ships, which were visible through my glass two hours before they were seen entering the harbor, for it makes a thing fifty miles off as near and clear as if it were only five."

His discovery aroused the keenest interest. The citizens of Padua were astonished, and the Senate immediately doubled his salary and confirmed his appointment for life.

With his own hands, he now ground lenses with which he made a telescope magnifying thirty times.

With it Galileo swept the heavens, and the imaginary celestial spheres of the ancients came crashing to the earth past the possibility of reconstruction. By a single stroke he had expanded the universe to vast proportions. To his amazement he found that he could count ten times as many stars as he beheld with the unaided eye. Turning his "optic tube" upon the beautiful Milky Way, he resolved this band of mellow light into myriads of faint stars. Magic-like new worlds innumerable sprang into view. He examined the moon and found its rugged surface scarred by lofty mountain ranges and pitted with volcanic craters. He proved that Venus passes through phases, just as the moon does. Before the uncanny gaze of this earnest seeker after truth, the sun disclosed its spots and the period of its rotation. More important still, he discovered the four moons of Jupiter, and as he watched their movements from night to night, lo, he seemed to behold a miniature solar system after the pattern of the Copernican view.

But he had been treading upon dangerous ground. Storm-clouds were gathering. It was heresy against the teaching of Aristotle and the imaginary heavens of the church fathers, built at infinite pains, to find blemishes on the sun or to prove that the moon and planets are anything but perfectly smooth spherical bodies. Learned men refused to look through Galileo's glass for fear that the evidence of their senses might convince their understanding. Writing to Kepler, Galileo exclaimed: "Oh, my dear Kepler, how I wish that we could have one hearty laugh together! Here, at Padua, is the principal professor of philosophy whom I have repeatedly and urgently requested to look at the moon and planets through my glass, which he pertinaciously refuses to do. Why are you not here? What shouts of laughter we should have at this glorious folly! And to hear the professor of philosophy at Pisa laboring before the grand duke with logical arguments, as if with magical incantations, to charm the new planets (Jupiter's moons) out of the sky."

In 1610, Galileo left Padua, crossing the Apennines to become "Philosopher and First Mathematician to the Grand Duke of Tuscany" at Florence. At length, though not until more than twenty years had passed, the storm that had been brewing broke. The story of the aged scientist's humiliation and trial are too well known to need detailing here. Upon his release, he turned to the study of mechanics, the subject which first challenged his interest and the field in which he made his original and lasting contribution to the new-born science of modern physics. Here his passion for practical experiment, of which he was the first great apostle, found full play.

Just to keep the record straight, let us note that Simon Stevin, a contemporary of Galileo, discovered the law of the inclined plane, one of the six simple machines, and worked out the parallelogram method of combining forces. Archimedes, it will be recalled, had in the third century B. C. discovered the principle of the lever. But, aside from these, little exact knowledge regarding the motions of bodies and the principles underlying the operations of machines had been formulated. Here was a virgin field which had long been waiting for a master mind to bring forth its rich harvest.

Even as a young man, while kneeling in the cathedral to pray, Galileo's attention had been arrested by the swinging to and fro of the great lamp which hung from the ceiling. Using his own pulse beats as a measure of time, as nearly as he could determine, the swings of the lamp were all made in equal times, and this notwithstanding that they were constantly getting smaller and smaller. Here was an important law of physics and one which the Dutch physicist Huyghens soon after applied in the invention of the astronomical clock. Galileo himself utilized it in a device for counting a patient's pulse.

This discovery of the law of the pendulum was only a beginning. With an insight which stamps him as an original thinker of the first magnitude, Galileo seized upon the fact of momentum as the most significant quantity in the science of mechanics. Let us take time to consider what is meant by this fundamental property of a moving body.

Did you ever run into a lamp-post in the dark and as a vivid reaction to this unpremeditated experiment see all the stars in the constellations? If so, then you have had a painful illustration of what we mean by momentum. I recall, as many of you probably do, a story in an old school reader, entitled *The Professor in Shafts.* Coming to the top of a long steep hill, the professor argued with his coachman that his superior knowledge of the laws of motion would enable him to take better advantage of the various changes in the incline of the highway than the horse would be able to do. Reluctantly, the coachman unhitched the horse and put the professor in his place. However, the momentum of the carriage became too much for the technical skill of the theoretical master of motion. The constantly increasing velocity of the carriage, coupled with its greater weight, produced an effect which the professor, despite his weight of learning, could not overcome.

This effect we call momentum. It is closely associated with the idea of inertia, and inertia is the most fundamental property of all matter. Momentum is simply the inertia of a moving body, and Galileo was the first to perceive the law of its action.

Let us examine this idea of inertia further. If I leave some valuable object lying upon my desk and later discover that it has disappeared, I conclude that some one has overcome its inertia. A body at rest with respect to some particular system can not get into motion of itself. We say *some particular system* because, as we shall see, motion is always relative to something else. There is no possibility of demonstrating either absolute motion or absolute rest, but of this more later.

It is equally true that a body in motion tends to continue in motion. If it meets with no resistance, its motion will continue forever. We see no illustration of this sort of inertia here on the earth, because we can not escape the fact of gravitation, friction and air resistance. That is, we have no case of perpetual motion. The heavenly bodies afford beautiful examples of this aspect of inertia. Although Galileo did not generalize this conception to include all bodies, those outside of the earth's influence as well as those in it, he saw it clearly enough. This is shown by his calculation of the path of a projectile, in which he assumes that the horizontal velocity of the shot is uniform after it leaves the muzzle of the gun, barring, of course, air resistance. The motion which the missile acquires from the explosion of the powder would cause it to move forever, could gravitation and air resistance be eliminated. It is interesting to note, too, that a bullet fired with a high horizontal velocity will fall to the ground just as quickly as though it were dropped from the muzzle of a gun and did not have any horizontal velocity at all.

All of this with reference to the inertia of a body is simply a statement of Newton's First Law of Motion. Although Galileo did not formulate these facts into a law, there is no doubt about his having discovered them. And what we must not lose sight of is the outstanding circumstance that he based his conclusions upon experimental evidence. He began to lay the foundations of a real science of physics.

Momentum is defined as the quantity of motion a body possesses. Galileo demonstrated that velocity is a factor in determining the magnitude of this quantity. He measured this magnitude by the weight times the velocity, just as we do to-day, with the exception that we substitute the term mass for weight. The concept of mass, an inalienable property of matter; of which we shall have much to say at various places in this book, was originated by Newton. Galileo apparently did not see that while the weight of a body will vary at different places, its mass, regarded as the quantity of matter it contains, never will. As we shall see when we come to consider relativity, there are other meanings for the term mass, however, and it is not an invariable quantity as was formerly supposed.

Inertia is such a fundamental property of matter and so important to the science of mechanics that we shall cite a few other examples. Did you ever try to keep your balance when standing in a rapidly moving subway train as for some unknown reason it was suddenly brought to a stop, that is, to rest with respect to the rails? If so, the degree of your chagrin at having been involuntarily precipitated into some one's lap may be taken as a measure of your inertia, or what is the same thing in this case, your momentum. Or, if you had instead been sitting, facing in the direction the train was moving, and felt yourself sliding forward on the seat, the bracing of your feet to prevent a near catastrophe was a move to overcome your inertia. You were experiencing the property which tends to continue a body in a state of motion when once it has got under way. If you stop to think of it, there is nothing in the constitution of a body itself which should increase or decrease in the slightest degree its motion. Motion of some sort is as natural as the state of rest. Our earth-bound sense and experience prevent our appreciation of it. That is all.

When a train has been brought up to speed, its momentum largely keeps it going. It does not immediately stop when the power is turned off, but only when the brakes have been applied and the friction and air resistance have overcome its inertia. If you have ever been on the end of the line in the old-fashioned game of cracking the whip, you know what a wonderful and fearful thing momentum may sometimes be. The distance to which the athlete throws the discus is determined by the quantity of motion he is able to store up as he whirls the circular plate about his head. When he throws it, too, he simply lets go. The inertia of the moving discus tends to carry it off in a straight line tangent to the curve in which it moves. Likewise, should the gravitation of the sun suddenly cease, the planets of our system would move off in lines tangential to their orbits. We used to say that, unless they encountered the gravitational influence of some other heavenly body, they would move in straight lines forever. Since the vogue of Einstein, however, we are inclined to believe that they might circumnavigate this finite universe and come back, after inconceivably long periods, to their starting-points. I once heard a noted reformer say that a miracle is nothing but the suspension of a natural law. As illustration, he stated that every time he lifted his feet from the ground he temporarily suspended the law of gravity, utterly oblivious to the fact that he still felt the sensation of weight. However, had this distinguished person's diagnosis been correct, the inertia of his body developed by the earth's velocity of rotation, a form of inertia which we call centrifugal force, would have hurled him into space to move forever after as some sort of a heavenly body.

And again, the momentum, or inertia, stored in a massive fly-wheel keeps the machinery running smoothly and without vibration. A rolling hoop, a spinning top or a bicycle are wonderful examples of inertia. In each case these bodies resist with a force altogether greater than one would expect from their respective weights any tendency to change the direction of the axis of rotation. You know with what perfect sense of stability you sit upon the seat of a rapidly moving motorcycle. You are enjoying the security afforded by the inertia of a rotating body. The gyroscope in its marvelous applications utilizes this principle. And just as Galileo determined three centuries ago, the magnitude of this effect is measured by the weight, or mass, of the body and its speed.

Let us examine these two factors a little more. You have stood on the pier as a ferry-boat has come to dock. Its motion is exceedingly slow, and yet as it strikes the pier its timbers are made to shiver with the impact. The quantity of motion is great, although the velocity is slight. A rowboat with many times this velocity would have scarcely any perceptible effect. A massive body in motion produces an effect in which the mass is a large factor. On the other hand, a bullet with high muzzle velocity has a relatively large momentum, although its mass is small. However, the bullet, and also the ferry-boat in a relatively less degree, possesses what we call kinetic energy, which must not be confused with momentum. This we shall make clear later.

So much for the analysis of the idea of inertia and Galileo's contribution in this field of mechanics. But this was only a beginning. A host of problems had long been waiting for the coming of a man with a keen mind and the capacity for clear thinking. I fancy, too, that this pursuit of truth was fascinating. Here was virgin territory—the opportunity for original discovery. And with Galileo it was always by the experimental method.

Galileo now passed on to a study of the motion of falling bodies. One of his earliest experiments had been that at the Leaning Tower of Pisa. His work soon showed him that there is some constant factor in the motion of a body falling under the influence of the earth's apparent attraction. This pull of the earth is different from the impulse, for instance, imparted by the explosion of gunpowder in the barrel of a gun. One is constant and accumulative. The other is instantaneous. It acts for a moment and then is gone. Should one inadvertently plunge from the upper floor of a skyscraper, he could suffer from no illusions. There is not a particle of ground for the slightest suspicion that this influence which we call the force of gravity would abate one iota of its merciless grip. It is only common sense to assume that this never-ceasing action should manifest itself in some sort of constant effect. Galileo determined to discover with mathematical exactness what this effect might be.

Down the center of an inclined plane, a board twelve yards long with one end resting on the ground and the other raised to a certain distance, he cut a smooth trough one inch wide. Down this trough, he rolled a highly polished brass ball. Having no clock with which to measure the time intervals, for his discovery of the law of the pendulum had not then been applied in a practical mechanism, he arranged a pail of water with a small opening in the bottom fitted with a plug. He allowed the water to flow into a cup, timing the beginning and end of the flow for the exact duration of his experiment. The weight of the water would give a measure of the time interval.

From many experiments, repeated over and over with the height of the plane adjusted for various angles of inclination, he determined that for any given angle the time-rate at which the ball gained speed remained constant. Here was the fixed quantity which he had anticipated. He called it acceleration, just as we still do to-day. The use of the inclined plane was simply to reduce the velocity. The principle was the same as though the body had fallen freely. Galileo also worked out the mathematical relationship existing among the quantities involved, namely, the distance passed over, the time, the velocity and the acceleration. These constitute the well-known laws of falling bodies, with which every student of elementary physics is so well familiar.

For a freely falling body, Galileo determined that the acceleration is approximately thirty-two feet per second per second. Let us explain why we say "per second per second." The velocity gained is at the rate of thirty-two feet per second in one second of time. That is, for a body falling from rest the velocity at the end of the first second will be thirty-two feet per second. In the next second it will gain thirty-two feet more of velocity, making the total sixty-four feet per second, and so on. It should be observed, however, that these numbers do not represent the distances passed over. For instance, the distance covered in the first three seconds is the average velocity for the whole period times three. And the average velocity is half of ninety-six. That is, it is the final velocity, ninety-six, plus the initial velocity, zero in this case, divided by two.

This gives one hundred and forty-four feet for the distance covered in the first three seconds.

Let us write down the form in which Galileo, in the year 1604, stated the result of his discovery: "I call a motion uniformly accelerated," he said, "when starting from rest its momentum, or degree of speed, increases directly as the time, measured from the beginning of motion." A present-day physicist could not improve upon that for clearness and conciseness.

Just a word about this quantity called acceleration. Acceleration is the chief characteristic of the present age. A distinguished American editor remarked the other day that whereas our grandfathers might miss a stage-coach and thereby possibly lose a week of time without being particularly disturbed, we swear now if we miss one section of a revolving door. Any one who has had his foot on the accelerator of an automobile, and that is practically every one, has had conscious experience of the speed mania which has taken possession of the race, and of America in particular. He has tasted the thrill of joy which comes from consciously directing a mighty force. If, mayhap, his wild ride has suddenly been brought to a halt, he has had a lively sense of the meaning of momentum. He, too, will not need much elucidation on the subject of negative acceleration, and he will have had an illuminating illustration of the fundamental laws of motion with kinetic energy thrown in for good measure, subjects which will be considered in the next chapter. As he surveys the sad plight of his wrecked automobile, the amount of distortion produced will be a fair index as to the quantity of work, in the physical sense, which has been done upon his machine. Finally, the cost of repairs will serve to emphasize the price which we are sometimes compelled to pay for this thrill of accelerated motion.

Suppose we return for a moment to the famous statement of Aristotle regarding the relative times, or velocities, of two falling bodies of different weights. Possibly his answer was not so ridiculous after all. It may be simply the common-sense view. Should not the earth's attraction be one hundred times as great for a mass of one hundred pounds as for a mass of one pound? If not, its weight would not be that many times greater. Of course this is true, but it is also true that the resistance which the heavier body offers to the earth's pull is one hundred times as great as is that of the lighter body. For not only does the earth pull the body, but the body also exerts an equal and opposite pull on the earth. This is the essence of Newton's Third Law of Motion. Although Galileo did not formulate it, this was the unknown factor in the experiment which brought the supporters of Aristotle's dictum to grief.

As already indicated, some of Galileo's most notable work in the field of mechanics had to do with projectiles. His discovery of another fundamental principle enabled him to prepare a range-table for gunners. We have already mentioned the fact that a bullet fired from a gun in a perfectly horizontal direction will strike the ground just as quickly as though it had been freely dropped from the muzzle. That is, the pull of the earth will have just as much effect in producing a downward velocity as though the bullet did not have the horizontal velocity at all. If a marksman were to aim his gun in a perfectly horizontal direction, making no allowance for the earth's pull, he would not hit the target. The gunsights have to be adjusted so as to elevate the barrel just enough to overcome the influence of gravity.

Now this is all in illustration of the discovery of Galileo that the momentum imparted to a body in one direction will not be in any way affected by another momentum which it may acquire in a direction at right angles to the first. Each force will have precisely the same effect as though the other force were not acting at all. Newton later rediscovered this and formulated it as his Second Law of Motion. However, Galileo was the pioneer.

Galileo was the first discoverer, too, that the path of a body moving with a uniform horizontal velocity and subject to the earth's pull will be a parabola. This is because, while the velocity in one direction remains constant, the velocity in a direction at right angles continually increases by a definite amount in each second.

To Galileo we probably owe the first thermometer. It was a crude affair, but correct in principle and gave an approximate indication of surrounding temperatures.

We now define *force* as that which tends to produce, to change or to destroy the motion of a body. Galileo, above all else, is to be remembered as the one who first introduced this idea as a factor in the rate of change of momentum. Dying in the same year in which Newton was born, Galileo was a most worthy forerunner of the eminent physicist of the British Isles. In his experiments and discovery of natural laws, he had provided a rich fund of exact knowledge for his great successor. More than any one else before the coming of Newton, he enabled those of his time and after to catch wonderful glimpses of some of the fundamental realities of the physical world.

In this brief and sketchy review, we have now journeyed from that first discoverer of many thousands of years ago to the man whose researches provided the basis for an era of physical science in which we still live, for despite the coming of Einstein the principles of Newtonian physics for all practical purposes yet hold sway.

CHAPTER III

THE AGE OF NEWTON

SPIRIT OF THE AGE—FUNDAMENTAL CONCEPTIONS—IDEA OF MATTER—INERTIA MOST UNIVERSAL PROPERTY OF MATTER—IDEAS OF TIME AND SPACE—THE TERM MASS—INERTIA, A MEASURE OF FORCE AND MASS—TWO NOTIONS OF MASS—THE CONCEPT OF ENERGY—THE IDEA OF WORK—POTENTIAL AND KINETIC ENERGY—ILLUSTRATIONS—POWER—NEWTON'S LAWS OF MOTION—GALILEO, THE FORERUNNER OF NEWTON—LIFE OF NEWTON—FIRST LAW AND ITS MEANING—SECOND LAW—INTERPRETATION—THIRD LAW—ILLUSTRATIONS—RELATION OF THIRD LAW TO PLANETARY MOTION—NEWTON INTERPRETS KEPLER'S LAWS—EARLY CONCEPTION OF LAW OF GRAVITATION—LAW OF GRAVITATION EXPLAINS MOON'S MOTION—EXTENDS LAW TO INCLUDE WHOLE SOLAR SYSTEM—STATEMENT OF LAW—DISCOVERY OF NEPTUNE—A GALAXY OF LESSER LIGHTS—TORRICELLI AND THE BAROMETER—GUERICKE INVENTS THE AIR-PUMP—BOYLE AND GAS PRESSURES—HUYGHENS—INVENTION OF PENDULUM CLOCK—THEORY OF THE ETHER—GROWTH OF A THEORY OF LIGHT—DISCOVERIES PRECEDING NEWTON—COMPOSITION OF SUNLIGHT—EXPLANATION OF COLOR — WORK OF YOUNG — EXPERIMENTS — THE NATURE OF LIGHT—NEWTON'S CORPUSCULAR THEORY—WAVE THEORY OF HUYGHENS—MEANING OF DIFFRACTION—YOUNG AND THE INTERFERENCE OF LIGHT—CORROBORATION OF WAVE THEORY BY FRESNEL — POLARIZED LIGHT AND TRANSVERSE VIBRATIONS—TRIUMPH OF WAVE THEORY—THEORY OF THE ETHER—DIFFICULTIES OF THE CONCEPTION—VELOCITY OF LIGHT—CONTRIBUTION OF NEWTONIAN EPOCH.

THE period of scientific history dominated by the thought of Sir Isaac Newton, who lived from 1642 to 1727, was characterized by a wide-spread spirit of keen and intelligent inquiry. The work of Copernicus, Brahe, Kepler and Galileo coupled with the writings of René Descartes and Francis Bacon had stimulated a general interest and had prepared the ground for the discoveries of such giants as Newton, Boyle, Hooke and Halley in England, and Leibnitz, Huyghens, Torricelli, Pascal and Guericke on the Continent, not to mention others. Already William Gilbert, of whom we shall speak later, had made a beginning of the science of electricity. This period, too, marked the founding of the learned societies which for nearly three centuries have been focal points for scientific research and the spread of new knowledge. Chief among these were the Royal Academy of Sciences in France and the Royal Society for the Advancement of Learning in England. The time was ripe for big things and a great leader, and both came.

SOME FUNDAMENTAL CONCEPTIONS

At the very outset of this formative epoch in the growth of physical science, we shall need to familiarize ourselves with certain basic ideas, indispensable to the mechanics of the subject. Most of them had their origin in this period. However, the meanings of some have changed with the clarification of knowledge resulting from new discoveries. In a number of instances this evolution has been little short of revolutionary. The mere mention of the Einstein theory is sufficient to make this clear. To trace the origin of these ideas and the changing view-points in the light of scientific discovery is a fascinating pursuit.

Suppose we begin with the idea of matter. During the materialistic period of the eighteenth century, matter was supposed to be the most important concept with which physics has to deal. It was defined as that which occupies space and possesses weight. The mere mention, however, of the terms of space and weight, in view of the turmoil of ideas provoked by the new physics, shows how much water has passed under the bridge since this definition was formulated. As will be shown in a later chapter, too, matter is now regarded as electrical in nature, and it is not indestructible as such. To get Newton's idea of matter, read the following:

> "It seems probable to me that God in the beginning formed matter in solid, massy, hard, impenetrable, movable particles, of such sizes and figures, and with such proper-

ties, in such proportions to space, as most conduced to the end for which He formed them; and that these primitive particles, being solids, are incomparably harder than any porous bodies compounded of them; even so very hard as never to wear or break in pieces; no ordinary power being able to divide what God Himself made one in the first creation."

Could Newton, with the vision and knowledge of a twentieth-century physicist, have gained the peep within the atom that we have to-day, he would have beheld the most porous unit in creation. Between its constituent parts are vast dreary wastes of space comparable to those between celestial bodies. Eddington has recently said that, could we condense the electrons and protons in the atoms comprising the body of an ordinary individual into a perfect solid, the product would be just visible with a microscope. Before such a statement of scientific fact the most vainglorious may well stand in awe and humility.

We can not disregard the idea of matter. Whatever its ultimate constitution, it has not been charmed away. It is very real. And of course matter has properties. A property is a characteristic. I recognize my friend by the color of his hair and eyes, his facial expression, his form and carriage and a dozen other properties. The most fundamental property of matter is inertia, already discussed in part and to which we shall refer often in succeeding pages. Another is impenetrability. It means that two bodies can not occupy the same space at the same time. By the way, too, let me remind you that we can not define this property without making use of both space and time. That is worth noting. Upon this fact of the indissolubility of space and time hangs much of the new physics. But let us illustrate. The other morning I witnessed the collision of two automobiles. Here were two bodies trying to occupy the same space at the same time. They came to the crossroads at the same instant of time. As the Einsteinian would say, their "world-lines" met, and they came to grief. Had it not been for this fourth dimension of time, the cars would have been all right. One could have occupied this space and then the other. But somehow the space and time elements could not be kept separate. Both cars were apparently traveling along the same dimension of time toward the same point in space. All of which only serves to emphasize that a body can not exist in space without also existing in time. Upon this fact depends the property of impenetrability of matter.

Now that we have mentioned time and space, let us consider Newton's view of these factors which figure so largely in human experience. In his immortal *Principia,* he says: "Absolute, true, and mathematical time, of itself, and from its own nature, flows equably without regard to anything external, and by another name is called duration. . . . Absolute space, in its own nature, without regard to anything external, remains always similar and immovable." That is, Newton regarded space and time as two perfectly distinct and absolute entities, each existing in its own right and entirely independent of every other fact in the universe. I do not believe the drivers of those automobiles would agree with him. The ideas of space as empty nothingness and time as a flowing stream in which things happen are largely fictions of the imagination. If nothing ever happened, there would be no need of time. And, if there were nothing to put in it, we should have no use for space. This Newtonian conception of an absolute and eternal space and a simultaneous *now* as a separate and independent entity is at the bottom of a whole lot of this hubbub over relativity, as we shall consider again at the proper place.

Of course matter has many other properties, such as porosity, divisibility, elasticity, cohesion, mass and weight. Of these the most important is mass, a term coined by Newton to designate the quantity of matter a body contains. It is one of the most fundamental ideas in physics and will be worth a little closer examination.

For a long time the abstractions of space, time and mass constituted the principal ideas in the science of physics. It was believed that they give a complete description of the phenomena of motion. This belief led Laplace to assert that, given the law of gravitation and a knowledge of the distribution in space of the particles of matter comprising the primitive nebula from which our solar system evolved, it would be possible for a mathematical genius to derive therefrom the whole subsequent history of the world. We have since traveled a long way from that mechanical conception of the universe.

But to come back to the term mass. With that wonderful insight that characterized the mind of Newton, he saw that a body possesses some constant property which never deserts it. The body might be taken anywhere in the universe, and this quantity would remain the same. Its volume might expand or contract; its weight might change; but something about the body would remain unchanged. Already it had been determined by a Frenchman, Jean Richter, who experimented with a pendulum in Paris and at the equator, that the length of a pendulum which would beat seconds was not quite the same in one place as in the other. Huyghens, to whom this fact was reported, clearly saw that the weight of the pendulum must vary in the two places, a circumstance now well known to every high-school student of physics. That is, the pull of the earth upon the pendulum is less at the equator, because a body is there a little farther from the earth's center. Huyghens also recognized that there is something about the pendulum which remains constant in being carried from one place to another, for the experiments were performed with the same pendulum in both places. In the first paragraph of his *Principia*, Newton crystallized this idea in the following language: "The quantity of matter is the measure of the same, arising from its density and bulk, conjointly. . . . It is this quantity that I mean hereafter everywhere under the name of body or mass."

Now that the thing has been stated, it is clear enough. While weight varies, mass does not. The quantity of matter always remains the same. The pull of the earth upon a given body will change as its location changes, for, since the earth is an oblate spheroid, the distance of the body from the center of attraction is not everywhere the same, and as we know, the gravitational influence changes with the distance. Let us also note that the amount of this change in weight is always the same for a given body between the same two points on the earth's surface. This could not be so if the mass of both the body and the earth were not invariable.

Let us illustrate this in another way. Suppose we place a mass of gold in one pan of a lever, or beam, balance and exactly counterbalance it with gold weights. We say gold because this metal will be practically free from chemical changes, and in an experiment of this kind we are not limited. We can just as well have gold as any other metal—even platinum for that matter. Now it must be clear that wherever we carry this balance the equilibrium will not be upset. The changing gravitational pull will affect one side of the balance just the same as it does the other. And this because the amount of matter on one side is the same as it is on the other. That is, the respective masses remain invariable. We might carry this balance to the moon, or to any other heavenly body, and the same would be true. However, if we were to attach the original mass of gold to a spring balance, the earth's pull upon the tension of the spring would change with changing location and therefore the weight registered would vary.

Thus far we have considered mass simply in its original significance, namely, the quantity of matter a body contains. However, there is another meaning and one that is seldom made clear by writers on this subject. It is related to the ideas of force and inertia. As already defined, force is that which tends to produce, destroy or change the motion of a body. That is, a force manifests itself in its effect upon motion. Of course, we have numerous instances of the interplay of forces which produce no motion—systems which are in equilibrium. However, we are not now concerned with them.

Now, as Galileo showed, the effect of a constantly acting force like that of gravity is to give velocity to a body, and the amount of velocity given in one second is called the acceleration. Thus a force which will give to one pound an acceleration of one foot per second per second is called a poundal. In the metric system, a force which will give to a mass of one gram an acceleration of one centimeter per second per second is called a dyne. Therefore, we measure force by the acceleration it will produce in a given mass. In other words, we say that the force is equal to the mass times the acceleration.

In giving acceleration to a body, it must be evident that the force has to overcome the inertia of the body, if it is at rest, and give to it momentum. Therefore, the inertia of the body is a measure, of both the force and the mass. For instance, if a given force will impart to two different bodies the same acceleration, the masses of the two bodies must be the same. In each case, the force overcomes the same amount of inertia, or opposition to motion. Thus, we may think of the mass of a body in terms of its inertia, and it is this meaning which is emphasized very much in the theory of relativity these days, but is seldom specified as such.

In this connection let us refer briefly to a point which will be considered more fully later. Einstein has shown that the mass of a body should increase with velocity. At the ordinary velocities obtainable here on the earth, this increase of mass is negligible and unmeasurable. Nevertheless, as velocities become many thousands of miles per second, the increase is large, reaching infinity at the velocity of light. However, this does not mean that the quantity of matter in a body becomes infinitely great, but that the inertia of the body, its opposition to motion, or to any further increase in its velocity, has reached a maximum. For this reason Einstein holds that the velocity of light is the greatest velocity possible to obtain anywhere in the universe. Otherwise, the mass of a body could be increased beyond infinity, which is an absurdity. As we shall see, experimental evidence confirms Einstein's contention.

If we could step off into space a few millions of miles, so far away from any gravitational influence that a body would have no weight at all, it would still require the same force to overcome its inertia and give to it a certain acceleration. This inertia is the measure of the mass. This quantity is often called inertial mass to distinguish it from gravitational mass, or the weight of a body. However, the two are proportional. If we divide the weight of a body by the acceleration produced by gravity at the place where the weight is obtained, we get a quantity which remains constant wherever we may go on the earth's surface, or upon any other heavenly body for that matter. This quantity is often taken as the mass.

Sir J. J. Thomson has shown that a moving charge of electricity possesses mass, that is, inertia, a fact which is of much importance in the electronic theory of matter.

It has already been remarked that in certain stars densities are enormously great, and density simply means the mass per unit volume. For instance, according to Eddington, material two thousand times denser than platinum actually exists in the stellar world. In the determination of these densities, one principle of the Einstein theory, as will be shown in due course, has an important bearing.

"Energy thus becomes the sole concept of modern physics," says Dr. Paul Heyl, a physicist of the United States Bureau of Standards. However, the idea of energy was longer in being developed, and for many years much confusion prevailed as to the precise meanings of the terms momentum, force and energy and the distinctions between them. This newcomer is recognized as the ability to do work and is of two general kinds, potential and kinetic. Let us analyze these ideas.

To define energy it appears to be necessary to know the meaning of the term work. I fancy that most of us think we know that already. However, suppose you were sentenced to hold supported in your hand raised above your head a five-pound weight for a period of thirty minutes, holding the weight perfectly still. Impossible, of course, but assume that you could. To be sure, your muscles would ache with the strain, but you would be doing no work in the scientific sense. You would be merely maintaining the potential energy of the weight. Again, suppose your automobile becomes stalled and you try to push it to the curb, but are unable to move it in the slightest degree. You have exerted force, but you have done no work. Work is said to be done only as a force acts upon a body so as to produce motion or to modify the motion of a body. The work is measured, too, by the force times the distance through which it acts. For instance, if you lift a weight of ten pounds through a vertical distance of one foot, you have done ten foot pounds of work. If this weight falls freely through a distance of one foot, it will do the same quantity of work upon the body which it strikes, manifested probably in motion, deformation and heat.

Now let us distinguish between potential energy and kinetic energy. In its simplest form potential energy is the capacity to do work which a body possesses because of its position. For instance, when a clock is wound up, the raised weight or the tension in the spring which drives the mechanism is potential energy. Likewise, the energy of the water at the brink of a fall is largely potential. However, being in motion, it already possesses some kinetic energy, or the energy which a body has by reason of its velocity. The motion of a pendulum illustrates beautifully both kinds of energy. When the pendulum is at the middle of its swing, its energy is all kinetic. At the end of the swing this kinetic energy has been translated into potential. Were there no friction or air resistance, the conversion would be one hundred per cent. perfect, and we should have perpetual motion. As the heavy weight of a pile-driver falls, its original store of potential energy disappears, becoming kinetic, which does work upon the pile by driving it downward and also by producing a certain amount of heat, which is lost. The measure of the energy in either case is the amount of work necessary to give the position or the velocity.

In earlier times, kinetic energy was designated as *viva vis,* or living force. It was the capacity to overcome resistance due to the motion of a body and was observed to disappear as the motion died away. A heavy weight resting upon a pile would exert pressure. However, if the weight were in motion, its capacity to produce results was enormously increased. This capacity was thought of as a living force. And indeed the energy due to velocity is large. Here we get an illustration of the difference between energy and momentum.

Let us consider a bullet weighing one ounce (one-sixteenth of a pound) and moving with a velocity of 1600 feet per second. The momentum is simply the mass times the velocity, or 100. However, the physicist measures the kinetic energy by one-half the mass times the square of the velocity. Working this out, we obtain 2500 foot pounds of energy. That is, if the energy of this moving bullet could all be utilized, it would be capable of lifting a mass of 2500 pounds one foot against gravity. Or it might be made to lift 25 pounds 100 feet. The kinetic energy is relatively large as compared with the momentum.

In accordance with a law which we shall consider soon, the momentum given to a bullet is precisely the same as the momentum imparted to the gun from which it is fired. It is a matter of common experience, however, that there is less danger in standing behind the gun than there is in front of it. And yet, if we were considering only the quantity of motion possessed by each, there would be no difference. But the momentum does not measure the work which a moving body is able to do. This is a function of the kinetic energy, which depends upon the mass and the square of the velocity. The kick of the gun represents its momentum, and of course it also possesses kinetic energy, but this is small because the backward velocity of the gun is small. Suppose in the above example that the gun weighed 10 pounds. Since its momentum is the same as that of the bullet, 100, its velocity in driving the gun against the shoulder becomes 10 feet per second. Calculating from this the kinetic energy of the gun, we obtain 15.625 foot pounds, large enough for comfort but vastly smaller than the 2500 foot pounds of the bullet.

There are a number of specific kinds of energy, such as mechanical energy, examples of which we have just been considering, heat energy, chemical energy, and electrical and magnetic energy. In every instance, however, we can trace the source of energy back to the sun. Should its radiant energy cease to flow forth, our earth would become a cold, dead, dreary world forever speeding on its way through the silent corridors of celestial space.

Suppose we illustrate with the falling water of a Niagara. It is the energy of the sun which evaporates the water from the sea; differences in temperature created by the sun drive the water vapor inland, where it condenses to rain to feed the falls. Without the sun this difference in energy levels could not exist. However, as we well know, this energy of the falling water may be made to generate electricity, which in turn is converted in part into useful heat, light, chemical effects and mechanical motion.

Then again, we may consider coal, our chief basic source of energy and power in the present age. Our coal measures once grew in forests of earlier geologic time. In that faraway period, even as now, the energy of sunlight in those marvelous chemical laboratories in the living cells of green leaves, took the carbon dioxide breathed in from the air and combined it with the water drawn through the roots to build the woody fiber of the plant or tree. Buried in swamps and covered with vast quantities of overlying sediments, these forests became metamorphosed into the crystallized sunshine which we call coal. Other examples might be given.

At another point we shall return to this subject of energy and the law of the conservation of energy, which says that energy can neither be created nor destroyed but that it can be changed from one form to another. In particular, we shall wish to know the source of the solar fires and how long it may be before we shall have to close out business on this planet for lack of the wherewithal to keep it going. What, too, of the degradation of energy, which we are often told will some time cause our differences of energy levels to disappear and convert our apparently vast sources of supply into an immense reservoir of latent but unavailable energy? However, when thoughts of this kind weigh heavily upon me, it always comforts me to think of the old lady who worried a great deal about what the world would do for light when the whales were all killed and we should have no more oil for our lamps.

A moment ago the term *power* was mentioned. It will be worth our while to get a correct notion of its exact significance, for this is often confused with energy and force. Power means the rate of doing work. It involves the element of time. If ten thousand tons of ore are to be hoisted from the hold of a ship, it will make no difference with the amount of work done whether this is accomplished in five hours or five days. However, the power of the motors required for the purpose will depend largely upon this time factor. One horse-power, the common unit, means doing work at the rate of 33,000 foot pounds per minute. That is, this amount of power will lift 33,000 pounds one foot against gravity in one minute. Or it will lift 3300 pounds ten feet in that time. The kilowatt, the electrical unit, is equal to about one and a third horse-power.

One other thought in passing, to which we shall return: We now know that energy, like its common form, which we call matter, possesses this fundamental property of inertia. From this fact, as we shall see, some rather startling conclusions are drawn, conclusions altogether at variance with the ideas of nineteenth-century physics.

NEWTON'S LAWS OF MOTION

Newton formulated three Laws of Motion which are among the most important foundation-stones of the classical physics. They are the very basis of the science of mechanics. However, as we have seen, the first two of these laws had been discovered by Galileo. This was Galileo's most important contribution. True, his brilliant illumination of the Copernican system, his invention of a practical telescope, his discoveries in astronomy and his observations on the pendulum are of more superficial interest, but these never would have founded a science of physics. Mechanics was the subject which arrested the attention of his early years, and to it he returned in his old age, when his sight had become too poor for work with the telescope and when his enemies had embittered his life and done their best to thwart his efforts in other fields. Without knowing it, his most enduring work was to be done in these last years.

First, just a word at this point regarding the life of Newton. As though the mantle of Galileo were to fall upon him, he was born in 1642, the year of the great Italian's death, even as Galileo himself had been born in the year which marked the passing of Michelangelo. Sickly as a child and showing no great aptitude for scholarship in his youth, he gave little promise either of the fulness of years which was to crown his active life or of the genius which he was to display even as a very young man. Educated at Trinity College, Cambridge, from which he was graduated in 1665, it was the study of mathematics there which roused his sleeping powers. Euclid he found exceedingly easy, and the geometry of Descartes he mastered without serious difficulty. It was at this period that he formulated a binomial theorem, familiar to all who have studied algebra, and shortly after he began the development of his mathematical theory of fluxions, which grew into the infinitesimal calculus, an instrument without which much of his later work would have been impossible. At twenty-seven he became professor of mathematics at Cambridge, a chair which he held for many years. After his discoveries had made him famous, he was appointed Master of the Mint, a position carrying a munificent salary and which he held for thirty years. During the last twenty-five years of his life he was president of the Royal Society. Queen Anne knighted him, and in his later years he was much in favor at Court. Early in 1727, at the time when Benjamin Franklin was a printer's lad in London, he died, rich in years and honors, and not poor in worldly goods.

Now let us state Newton's first law. It says: *"Every body tends to continue in its state of rest or uniform motion in a straight line unless it is acted upon by an outside force."*

Here we are coming into contact again with that inescapable property of inertia, for this first law is simply a statement of that fact of matter and energy. Ignorance of it, however, gave the ancients a great deal of trouble. Earth-bound as they were, they believed some force was necessary to maintain motion. Even Kepler imagined some sort of a backward propulsion, as though radial spokes might emanate from the sun, to shove the planets along in their orbits. He could not see that a body once in motion, however it may have obtained that motion, is powerless of itself to abate this state in the slightest degree. A planet speeds on and on because it can not help itself. Force would be necessary only to stop its motion or to change the direction of it. Newton for the first time clearly saw that what a planet needs to keep it in its orbit is a deflecting force. Otherwise, it would fly off along a tangent to the curve in which it moves. That was his first step in arriving at a conception of a law of gravitation.

Of course, we have an abundance of examples of bodies which remain at rest, that is, at rest with respect to the earth. However, there is no body which is absolutely at rest or, so far as we are able to demonstrate, partaking of absolute motion. What with the rotation of the earth on its axis, its revolution about the sun and the motion of our whole solar system through space, all of us, nevertheless, are continually enjoying a lot of free rides of which we are totally oblivious. I think we shall agree that nothing on this "vale of tears" has the satisfaction of perfect rest. Even the atoms and the molecules are in a state of incessant motion.

Newton, to be sure, was concerned only with a practical world, and for the realization of his law he was compelled to imagine an ideal case. If we could step off into space some million of miles, or rather we should say billions of miles, away from any heavenly body which might exert an attraction, or, to be more in accord with the present view, produce a gravitational warp in space, an object might stay put. It would need nothing to support it, and it would suffer no motion in any direction. Furthermore, could we be mounted on a body so ideally located and sufficiently massive as to afford some reaction to our muscular efforts, we might hurl a projectile into space and enjoy the infinite satisfaction of feeling that it would move on forever. Newton would have added "in a straight line," of course assuming that it did not come near any heavenly body. However, if, as Einstein says, this universe of ours is finite and space is curved, our projectile would sometime in the eons of eternity return to its starting-point. Newton guarded against the possible error of assuming such an ideal example by saying that a body will continue in motion unless acted upon by an impressed force, for he knew that such external forces are inescapable.

Let it be noted, too, that this first law carries the definition of the term force. It implies that a force is that which overcomes inertia. If sometimes seems that, if we could get well rid of this ubiquitous quantity of inertia, the universe might be a more enjoyable dwelling-place. However, a little thought shows that this apparently happy state of affairs would in all probability spell chaos, which after all might not be an unmixed evil. One of the best examples of inertia I have ever encountered is that exhibited by a class of students in opposing my efforts to teach them physics.

Now for the Second Law of Motion. Although Galileo may be credited with its discovery, he only dealt with one special case and did not see the law in its completeness. Again let us state the law: *"Change of momentum is proportional to the impressed force and takes place in the direction of the straight line in which the force acts."*

Stripped of its verbiage, this simply means that the velocity given to a body depends upon how great the force is and that the direction of motion will be in line with the direction in which the force acts. It also means that no matter how many forces may be acting on a body each will have the same effect as though the others were absent. Of course, the total effect will be the result of the combination of all the forces. Still, each force will have had its definite and precise influence. This is the aspect that Galileo saw. He realized that one force acting at right angles to another will have no effect in changing the momentum produced by the other force. It will only influence the direction of the resulting motion.

This was the idea which Newton was to utilize in his development of a law of gravitation for the solar system. He saw that a constant force directed from a planet toward the sun would serve only to produce a continual change in the direction of the planet's motion, giving to it a curved path. The inertia of the planet, expressed in his first law, would keep the planet going.

However, before going further, let us have several examples of this law. The change of momentum, or the acceleration, produced in a freely falling body is proportional to what the orthodox physics of yesterday termed the force of gravity at the place where the body falls. This will vary slightly over the surface of the earth, and on different heavenly bodies the variation will be considerable. On the moon, for instance, a falling body would gain velocity at only a sixth of the rate that it does here. In passing, let it be noted, too, that a person's weight would be decreased in the same ratio. Then, assuming that one possessed the same quantity of muscular energy as on the earth, just think of how he might bound about like a rubber ball, almost literally treading on air, if there were any air upon which he might tread! Again, on that star having a density of a ton per cubic inch, weights and accelerations would be enormous, however, always strictly in accord with the impressed force. On the Einstein view, the warp in space-time from such a concentrated quantity of matter would be extreme.

So much for one aspect of the law. Suppose you were to row a boat at three miles an hour directly across a river having a uniform current of four miles an hour. The boat will move across the river at the same rate as though it were in still water, and the current will bear it downward just as rapidly as though it had no other motion. That is, each motion will have its own appropriate effect. The path actually taken by the boat, however, will be a diagonal, the combined effect of the two motions, and the distance covered will be five miles.

Were you ever so imprudent as to try to jump from a moving trolley car or other vehicle at right angles to the direction of motion? If so, much to your discomfiture, you discovered, when your feet struck the pavement, that your body was under the influence of more than one motion at the same time. Your feet came to rest, but the rest of your body continued to move forward with the same velocity as that of the car from which you jumped, and you measured your length on the pavement, probably congratulating yourself that you did not suffer a fractured skull. After such an experience, too, one has little difficulty in realizing the truth of Newton's first law, and his comprehension of inertia, momentum and kinetic energy are in direct proportion to the damage done. Incidentally, the second law has had a verification.

Probably all of you have seen that industrious individual who at the show or on some busy corner of a crowded thoroughfare spins his tops and gyros, making them perform all sorts of marvelous stunts. As he rakes in the shekels, he tells you, too, that his spinning gyro absolutely defies the law of gravity and that no scientist wise enough to explain its action has ever appeared. As a matter of fact, this device affords a beautiful illustration of the First and Second Laws of Motion. The inertia of the spinning wheel tends to keep it spinning with its axis of rotation constantly pointing in the same direction. At the same time the attraction of the earth pulls the gyro downward with accelerated motion tending to make it rotate about another axis at right angles to the first. The result is a new movement, which utilizes both motions and prevents the mechanism from falling. The gyro, being under the influence of two motions at the same time, can not act as though it were under the influence of only one. In other words, it moves in accordance with the Second Law of Motion. The gyro-compass and the ship stabilizer are wonderful applications of these principles.

Newton amplified the first two Laws of Motion and added a third. This last is short. It says: *"To every action there is an equal and contrary reaction."* That is, forces can not act singly. They are always in pairs. You can not exert a pull, unless you have something to pull against. Suppose you attach a spring balance to a hook in the wall and pull until the balance registers fifty pounds. You pull on the balance with a force of fifty pounds and so does the hook. If it did not, you would come to grief with a backward motion, which might cause you to see stars. The action and reaction are equal and opposite.

Again, you rest your weight upon the floor, and the floor reacts with a force equal to your weight. If it did not, the floor would give way, precipitating you into the story below and possibly calling upon the insurance company to make good on its policy. In a succeeding chapter, we shall show that this reaction of the floor is due to the constant impacts of myriads of rapidly moving molecules upon the soles of your feet.

Of course, you never tried to do so foolish a thing as to jump from a swing. You know that you could not get the proper reaction and that there would be a disastrous fall. As a matter of fact, you would find it impossible to exert much force against a swing-board. However, when you jump from a spring-board, you get a wonderful reaction. This is built to utilize your effort to the full. But did you ever stop to consider that the momentum you give to the board is exactly equal to the momentum the board gives to you? This is the operation of the Third Law of Motion. We have already indicated that the momentum in the kick of a gun is the same as the momentum given to the bullet. The action and reaction are equal and opposite. However, let it be emphasized again that because of the high velocity of the bullet its kinetic energy, which determines the amount of work it can do, is vastly greater than that of the gun. The amount of inertia to be overcome in one case is much greater than it is in the other. This makes possible the high velocity for the bullet, and since kinetic energy depends upon the square of the velocity, we are dealing with a large factor.

Now I am going to say something which may make you feel quite important. When you take a running jump and kick your feet against the earth, the earth of course reacts to your effort. If you were to do the same stunt on thin ice, while the reaction would be there all right, it would not be of the proper kind. But what I meant to say is this: when you jump, the earth gives you, as the result of your action, a certain amount of momentum and sends you hurtling through the air. At the same time, you give an equal quantity of momentum to the earth. That is, you move the earth. Only an infinitesimal amount to be sure, but you move it. If you did not, the action and reaction would not be equal.

I am inclined to push this advantage further. However, I do not wish to give you too much cause for self-congratulation.

Sir Oliver Lodge tells us that this Third Law of Motion really implies the principle of the Conservation of Energy. That is, one can not get something for nothing. There is nothing truer in this world than that. One pays to the limit. The reaction can never be greater than the action. We shall see this cropping out in all sorts of places. For instance, in electricity the magnetic field of an induced current is always such as to oppose the motion that induces it. The greater the amount of current drawn from a dynamo, the greater the drag upon the engine that drives it. For that reason it is impossible to hook up a whole city lighting plant to a one-horse-power generator. To every effort, there is opposition. But no work is done unless motion is produced.

Let us take a classic example of this Third Law of Motion, that of the horse and cart. The horse pulls on the cart and the cart with an equal force pulls on the horse. How, then, can the cart get under motion? That has often seemed a puzzle. We forget that the horse and cart constitute a fixed system, at rest with respect to each other. All the action of the horse is not exerted on the cart. His feet act upon the earth, and the earth reacts against them. In this way the horse moves his body with respect to the earth, just as we do in walking, and pulls the cart after him.

The same applies to the action and reaction between a locomotive and the train it draws. Here is another action to take into account, that of the drive-wheels of the locomotive against the rails. When the rails are icy, we do not get the proper action and reaction. The energy of the expanding steam in the locomotive cylinder expends itself in spinning the drive-wheels without producing traction. Every automobilist has had this experience, sometimes to the tune of much inconvenience and tribulation of spirit. Incidentally, it throws light on the beneficent influence of friction. It is quite essential to the practical operation of this Third Law of Motion. True, perpetual motion might be possible, if there were no friction. But what good would it do? One could not even stand on his feet, to say nothing of using perpetual motion, and, if he once got into motion himself, he could never stop, short of direct impact with some massive body, and this would in all probability end his brief career. The reaction would be too great.

There is one particular case of the operation of this law which Newton found very useful in his explanation of planetary motion. Every one, sometime or other, has whirled about a weight attached to a string. The weight pulls on the string, and so does your hand. The action and reaction are equal and opposite. The pull of the weight is called centrifugal force (center-fleeing), while the pull of your hand is centripetal force (center-seeking). At every point of the string, these two forces are equal. You know, too, that, should the string break, the weight would fly off in a line tangent to the curve. Now, this experiment seemed to afford a striking similarity to the motion of a planet. The planet's inertia keeps it going, just as the slight movement of your hand keeps the weight going, and the action and reaction along the string corresponds to some attraction between the sun and the planet which all the while deflects the motion of the planet, making it follow a curved path. However, in the beginning, Newton was not sure that this was anything more than a happy guess.

It is easy enough to see how each of these classic laws is embodied in the explanation of planetary motion. We have also seen that they seem to be fundamental to a knowledge of motion in general. Had Newton done nothing else, his niche in the edifice of modern physics would be secure.

NEWTON AND THE LAW OF GRAVITATION

"No man liveth unto himself alone." Much less a scientist. Newton built upon the work of his predecessors, particularly that of Galileo and Kepler. Still, this in no way detracts from his genius. Without his keen analytical mind and capacity for original thought, the world would have waited much longer for the putting of its astronomical house in order.

It will be recalled that Kepler had discovered three laws of planetary motion. The first states that the form of each orbit is an ellipse, with the sun at one of the foci; in the second a line drawn from the sun to the planet is found to sweep out equal areas in equal times; while the third shows that the squares of the times of revolution of two planets are proportional to the cubes of their average distances from the sun.

As far as Kepler was concerned, these laws were merely statements of fact. At prodigious pains, he had established their truth. However, he had worked largely in the dark. He saw no explanation as to why they should be so. Let it be said, though, that neither Newton nor Einstein has fathomed the mystery of gravitation and determined its nature. With regard to Kepler, we mean that he did not arrive at any sort of an empirical way of accounting for the phenomena he had observed and the relationships he had established. He left this part of the problem precisely where he had found it.

Making use of the law for centrifugal force, worked out by Huyghens, Newton's first step was to show that for circular motion Kepler's third law would be true, provided there were an attracting force between the sun and the planet varying inversely as the square of the distance. This simply means that, were the distance between the two doubled, the force of attraction would be only one-fourth as great. If the distance were trebled, the attraction would be one-ninth and so on. This, Newton proved mathematically.

Newton next proceeded to extend this proof to elliptical motion. In fact, he showed that for any one of the conic sections—circle, ellipse, parabola or hyperbola—this relationship holds, always, however, on the assumption that the attracting force decreases with the square of the distance, and that the sun is in one of the foci. To do this, he was compelled to make use of the geometry of Descartes and his new method of fluxions, or calculus.

Finally, Newton proved that this sweeping out of equal areas in equal times is a direct outcome of an attracting force located at one of the foci and varying inversely as the square of the distance. This does not mean, however, that the planet moves in every portion of its orbit with the same speed, for its distance from the sun varies during the year, or one revolution. When it is near to the sun, its velocity is greater than when it is more remote. One of the important bits of evidence in support of the Einstein theory hinges upon this fact.

To picture the form of an ellipse, securely stick two pins in a piece of paper a short distance apart, say a half an inch. Over these place a loop of thread and, placing a pencil inside the loop, draw it taut. Now describe a complete curve, always keeping the thread drawn tight. You will have an ellipse. The locations of the pins will be the foci.

In the case of the earth, the distance across the orbit is approximately 186,000,000 miles and the distance between the foci about 3,000,000. This does not come far from being a circle. That is, the eccentricity of the orbit is small.

Newton's procedure to date affords an excellent example of the method of establishing a theory. He started with the hypothesis, supposition, that an attracting force from the sun, located at one of the foci, would account for the fact of Kepler's Laws, provided this attraction should decrease as the square of the distance increased. Then, he proceeded to prove mathematically that such a set of conditions demanded Kepler's Laws for their satisfaction. Thus, he had established a theory of gravitation. His next task was actually to prove in a specific case that the figures of measurement fitted the theoretical calculations. Then, he would have a law.

Newton had calculated what the effects of his hypothetical force would be. But was there actually such a force extending outward to the planets? We know to-day that it is not necessary to assume such a force. The facts of planetary motion can be accounted for in another and, in many respects, more satisfactory way. In the state of mathematical and theoretical science of that time no course seemed open other than to assume and prove so far as possible the existence of such a force. This, Newton proceeded to do.

The fact of the earth's attraction for bodies on and near its surface had been a matter of observation for centuries. Indeed, we saw that this was probably one of the first physical forces discovered by primitive men. Galileo had known that it was the force of gravity which caused his brass ball to roll down the inclined plane and pulled his projectiles to the ground. But the world waited for the genius of Newton to perceive that it might be this same force that holds the moon in its orbit. It occurred to him that the moon, too, might be a falling body, obeying the selfsame laws as those established by Galileo for bodies on the earth. To determine whether this might be true was a matter of comparatively simple calculation. His great ability as a mathematician had been displayed in his work on Kepler's Laws.

Newton started with the known astronomical fact that the moon's distance is equal to sixty times the radius of the earth. Now, a body at the earth's surface falls 16 feet in the first second. If, in accordance with Newton's theory, this attracting force decreases as the square of the distance increases, the moon should fall away from a straight line toward the center of the earth 1/3600 of 16 feet in a second. This amounts to 16 feet per minute. Newton made the calculation and found that the distance the moon falls away from a straight line in a minute was apparently only 14 feet. Keenly disappointed, he put his work aside, leaving it for sixteen years. Then, in 1682, Picard reported to the Royal Society a new measurement for the value of a degree on the earth's surface. This necessitated a recalculation of the earth's diameter, making it 3963 miles, instead of 3436 as had formerly been supposed. Newton immediately substituted the new value in his formulæ, and to his great joy found that the moon's motion agreed with his theory. Thus, the Law of Gravitation became a recognized fact, as far as our nearest neighbor was concerned. The same force which caused the mythical apple to fall in Newton's garden was shown to hold the moon in its orbit.

Newton now extended his law to include the motions of the planets and their satellites, the comets and the tides of the sea. In this work he showed that for mathematical purposes it is perfectly correct to assume that the entire mass of a planet is concentrated at its center. This was a tremendous simplification. Continuing his calculations with reference to the moon, he proved that the slight deviation of the moon's orbit from a true ellipse is strictly in accord with his law. Were the earth and the moon alone in the universe, this curve would be a perfect ellipse. However, the sun attracts the moon, as do also the other planets. Each produces a certain effect, all of which combined with the very much larger attraction of the near-by earth prescribes a path exactly in accord with the orbit of observation. Having conquered the solar system, he extended his law to include every member of the stellar universe. It was a great triumph, and until the coming of Einstein, no shadow was cast upon it. However, Newton's law in its practical workings is as true as ever. Einstein's law is larger, that is all. It includes Newton's as a special case, and it accounts for the effects of gravitation without assuming a hypothetical force.

Let us state the Law of Gravitation: *"Every particle of matter in the universe attracts every other particle with a force that varies directly as the product of the masses and inversely as the square of the distance."*

The first part of this law simply means that if we double, for instance, the mass, or quantity of matter, in one of the attracting bodies, the weight of that body will be doubled. If we could wave a magic wand and thereby suddenly double the density of the moon, not only would the attractive force between the earth and the moon be doubled, but the weight of every body upon the moon's surface would also be increased in the same ratio. If at the same time we should double the distance between the earth and the moon, this factor would diminish the attractive force to one-fourth, making the resultant attraction due to the two effects one-half its original value. However, the increased density of the moon would still continue to double the weight of bodies upon its surface.

Experiments with the pendulum by Newton and his successors have shown that gravitation is independent of the nature of the material. No matter what it is, the attraction, or whatever it may be which causes two bodies to tend to gravitate toward each other, depends only upon their respective masses and the distance between them.

A most beautiful confirmation of the law occurred something less than a century ago in the discovery of the planet Neptune, the outermost member of our little solar group. Ever since the time of Newton, astronomers had been troubled by certain deviations in the path of the planet Uranus about the sun. This planet did not follow the precise orbit dictated by the law of masses and inverse squares. Either the law was at fault or an unknown body existed in the heavens. Two astronomers, Adams, an Englishman, and Leverrier, a Frenchman, each independently of the other and purely on the basis of the truth of Newton's principles, worked out the precise mass, position and orbit of a theretofore undiscovered planet which would produce just the deviations observed. Leverrier, completing his calculations first, sent word to the observatory in Berlin that if its telescope were pointed to a certain spot in the heavens this theoretical planet would be found. The test was made, and there was the planet. The finite mind of man had demanded for its understanding of a natural phenomenon this additional cog in the cosmic mechanism, and forthwith it became a fact of scientific discovery. Science affords no more sublime instance of perfect faith in some sort of harmony back of creation.

Rutherford has shown that the law of inverse squares holds for the constituent members of the planetary group within the atom. But there the semblance ceases. No identity has been discovered between gravitation and the forces which hold the atom intact.

From Newton's great work, the *Principia,* published in 1686 through the efforts and financial assistance of the astronomer, Edmund Halley, we take the following:

> "We offer this work as mathematical principles of philosophy; for all the difficulty in philosophy seems to consist in this—from the phenomena of motions to investigate the forces of nature, and then from these forces to demonstrate the other phenomena; and to this end the general propositions in the first and second book are directed. In the third book we give an example of this in the explication of the system of the world; for by propositions mathematically demonstrated in the first book, we there derive from the celestial phenomena the forces of gravity with which bodies tend to the sun and the several planets. Then, from these forces, by other propositions which are also mathematical, we deduce the motions of the planets, the comets, the moon and the sea. I wish we could derive the rest of the phenomena of nature by the same kind of reasoning from mechanical principles; for I am induced by many reasons to suspect that they may all depend upon certain forces by which the particles of bodies, by some causes hitherto unknown, are either mutually impelled towards each other, and cohere in regular figures, or are repelled and recede from each other."

Lagrange, great French mathematician, said, "Newton was the greatest genius that ever existed, and the most fortunate, for we can not find more than once a system of worlds to establish."

A GALAXY OF LESSER LIGHTS

The half-century ending with the publication of Newton's *Principia* marked probably the most brilliant period in the history of science. We have nowhere anything else to compare with it, unless it be the period from the discovery of radioactivity toward the close of the last century to the present. However, we stand too near the scenes of this latter epoch to form a correct judgment. In that earlier time, a veritable heyday of notable triumphs, the foundations of the science of physics were laid. Great names adorn the pages of its record. It is worthy of comment, too, that the fundamental discoveries upon which the science of modern chemistry was built did not come for a century later. When Newton and his contemporaries were at work, alchemy was still in flower. Indeed, Newton himself was something of an alchemist.

That half-century which recorded Newton's most notable work also witnessed remarkable strides in the mastery of the physics of the atmosphere. From the time of Aristotle to that of Galileo about the only knowledge abroad regarding this medium in which the world seemed to be immersed was summed up in the famous aphorism: "Nature abhors a vacuum." The discovery that a suction-pump would not raise water more than about thirty-three feet at length began to cast some doubt upon the conviction as to Nature's scruples in this matter. Galileo knew that air has weight. He weighed a vessel filled with air and then forced more air into it, after which he weighed the vessel again. Nowadays we should exhaust the air from the vessel before weighing the second time, but Galileo had no air-pump. It was not invented until shortly after his death.

It remained for Torricelli, a pupil of Galileo and worthy successor as a teacher, to suggest an experiment which should settle for all time this question of atmospheric pressure. Of course, the water standing in a suction-pump, where the column reaches its greatest height, constitutes a crude barometer. In fact, a story is told of an early barometer with water as the medium. A long glass tube of fairly large diameter, open at the lower end and closed at the top, was filled with water and inverted in a cistern in the basement of a house. The upper end projected above the roof. Inside the tube had been placed a float in the shape of a small wooden man. On fair days this wooden man bobbed above the housetops and looked out upon his surroundings. On foul days he prudently kept out of sight. This, he repeated with great regularity, until the neighboring folk began to suspect that his master might be in league with evil spirits. How it was contrived to erect such a barometer, you should not ask.

Torricelli's claim to fame lies in his suggestion that mercury be substituted for water in the construction of a barometer. Knowing, too, the approximate density of mercury, he estimated that the height of the barometer column would be about one-fourteenth that of a column of water, not far from the correct figure. Viviani, a pupil of Torricelli, in 1643, actually carried out the experiment, and with great success. This was the first real barometer in history. In the space above the mercury in the tube is a vacuum, known as the Torricellian vacuum. If the mercury before use is properly freed from water vapor and enclosed gases, this is one of the most complete vacuums possible to get by mechanical means.

Every student of elementary physics is familiar with Pascal's Principle, which states with scientific precision the manner in which pressure is transmitted through an enclosed liquid. His important experiment with the barometer is not so well known. It constituted the second great step in the experimental process of exploring atmospheric pressure. Physicists had already conceded that it is this pressure that holds the mercury in the tube. Pascal argued that, if this is true, the pressure should be less at an altitude than at a lower level. This would manifest itself in a shorter column of mercury. To test his idea, he took the barometer reading on the ground and then at the top of a tall church steeple in Paris. The difference in the height of the two columns of mercury was not decisive. He therefore had his brother-in-law try the experiment by carrying a barometer from the foot of a mountain in Auvergne to the summit. To his delight, as he did so, the column of mercury fell three inches, thus giving a method of measuring altitude which has been standard to this day. Incidentally, this success laid the ghost of Nature's abhorrence of a vacuum.

At the same time, Otto von Guericke, whom we shall run across again in the story of electricity, to his own amusement and that of the populace, had been carrying out experiments on air pressure in Germany. Any one who has ever tried to draw vinegar or other liquid from a cask without first removing the bung knows that "it can't be done." Guericke proceeded to test this. He filled a wine-cask with water and tightly closed it. Then, with a carefully fitted brass pump connected with the cask, he tried to remove some of the water. The result was a bursting of the connections. These, he reinforced, after which with the aid of three strong men working at the piston he succeeded in extracting a little of the contents. However, as the liquid escaped, a hissing noise showed that air was at the same time entering the cask through small leaks.

These and similar experiments led Guericke to the invention of the air-pump. Astonishing things resulted from that first crude mechanism. On pumping the air from a closed container, he found that "a clock in a vacuum can not be heard to strike; a flame dies out in it; a bird opens its bill wide, struggles for air, and dies; fishes perish; grapes can be preserved six months in vacuuo." He it was, too, who invented the famous Magdeburg hemispheres, which for nearly three centuries have served to instruct and amuse many generations of schoolboys and girls. They consisted of two brass hemispheres, air-tight when fitted together and having a stop-cock for connection with the air-pump. When the air was exhausted and the stop-cock closed, it was found impossible to pull the hemispheres apart. The outside pressure of the air held them as in a vise. In other words, the kinetic energy of the rapidly vibrating molecules of air in ceaselessly beating against the hemispheres manifested itself in a marvelous degree of resistance, for many experiments show that this motion of the molecules is the source of the pressure.

With a set of hemispheres one and two-tenths feet in diameter, Guericke staged a demonstration before Ferdinand III and the court officials. This was in 1654. Only when four teams of horses were hitched to each hemisphere was it found possible to overcome the impacts of these exceedingly small particles of air. That air should have such enormous pressure was astounding. For millennia people had been constantly bathed in such an atmosphere with never a suspicion of the great burden which they were apparently carrying. Those were golden days of original discovery, days in which what we now regard as the simpler phenomena of Nature were for the first time laid bare. I sometimes envy the early workers in those virgin fields. Fresh paths opened on every hand; vistas of unexplored truth beckoned, and discoveries beyond the vision of the boldest dreamer were brought to light.

Of this theory of the motions of the molecules, of which of course Guericke and his associates had not the slightest inkling, we shall speak in another place.

An outstanding figure of this period and one who contributed much to chemistry as well as to physics was Robert Boyle, an Irishman born and seventh son of the Earl of Cork. He was fifteen years the senior of Newton and died in 1691, when the genius of his great contemporary was just reaching its zenith. Being a man of wealth and able to follow any pursuit which suited his inclinations, he chose the quiet and scholarly life of a scientific investigator. Aside from lacking the extreme eccentricity of Sir Henry Cavendish, he had much in common with that gifted recluse of a century later whose extraordinarily accurate work for the times contributed some of the most important discoveries to the growing sciences of physics and chemistry. Each devoted his life to science; neither married; each possessed wealth, Cavendish being one of the richest men in England; and both forever carved their names in the foundation stones of a great edifice.

Boyle was one of that brilliant coterie of self-made researchers out of which grew the Royal Society for the Advancement of Learning. Of their number was the great architect, Christopher Wren, and Robert Hooke, assistant to Boyle and for more than forty years curator of experiments for the Royal Society. In passing let it be noted that Hooke was a brilliant but unfortunate genius, who among a less distinguished group might have reached the pinnacle of greatness. As it was, he was overshadowed by the towering figure of Newton and is remembered to-day largely for his persistent opposition to his great contemporary.

Boyle's most important work was in the realm of gases. The law bearing his name is one of the best known discoveries in this field. Armies of high-school pupils have struggled with it. Any one of these pupils would tell you that the volume of a gas depends upon the pressure. Double the pressure and, if the temperature remains constant, the volume will be halved. Most of you know that the air pressure is nearly fifteen pounds per square inch at sea-level. This simply means that the total effect of the impacts of the molecules on a square inch of surface is able to support a weight of fifteen pounds. Let us give an illustration. When you travel in your car with the tires pumped to a pressure of thirty pounds, you have inside them what we call two atmospheres. One of these atmospheres counteracts the pressure of the air on the outside, and the other supports the car and its occupants. You ride in security and ease on a cushion of air whose resistance to the weight of the car and to the numerous bumps which are often received is maintained by the never ceasing impact of billions of molecules against the sides of the tire. The tire runs down because hosts of these elusive missiles succeed in getting by the tightly fitting valve. And you know with what cruel suddenness your joy ride comes to an end when a puncture permits the molecules to escape from their prison and seek the larger spaces of the outside air. The air left in the tire, then, just balances the outside pressure, and there is nothing left to support the car. Although you can not see it, the volume of the air formerly confined in the tire has doubled. This simply means that only half as many molecules are left to strike upon each square inch of surface. Thus, a tack or possibly a sharp stone has conspired with the imprisoned molecules to find a weak place in the wall of the tire and thereby work your undoing.

Boyle, too, first performed that famous experiment by which it was shown that a coin and a feather will fall together in a vacuum. This was a supplement to the historic experiment at the Leaning Tower of Pisa. How it would have gladdened the heart of Galileo, had he been able to witness it! It proved that, eliminating the resistance of the air, the force of gravity gives the same acceleration to all bodies, regardless of their weights. By placing a barometer under the receiver of an air-pump and exhausting the air, Boyle was able to show that it is the air pressure which supports the mercury column. As the air was removed, the mercury slowly fell. He, too, weighed a measured volume of air in a vacuum with greater accuracy than had ever been done before. As Guericke had done, he showed that sound will not travel through a vacuum. With an insight remarkable for the times, Boyle advanced the theory that heat is the result of the rapid agitation of the small particles of which he believed matter consisted. Here was the kinetic theory of heat two and a half centuries in advance of its later formulation.

Above all else Boyle was one of that small band of pioneers who insisted that scientific progress rests upon accurate and painstaking experimental work. This was the thing he loved most. "In my laboratory," he wrote, "I find that water of Lethe which causes that I forget everything but the joy of making experiments." In one of his books, he said, "The book of Nature is a fine and large piece of tapestry rolled up, which we are not able to see all at once, but must be content to wait for the discovery of its beauty and symmetry little by little, as it gradually comes to be more unfolded or displayed."

We have reserved for the last of this lesser group mention of Christian Huyghens, the "Dutch Archimedes," who, contemporary with Galileo in his boyhood and with Newton in his later years, supplied the most important connecting links between these two great men. Huyghens, too, was a founder of the science of modern physics. He distinguished himself alike in mathematics, physics and astronomy. His father was a man of means and a literary figure of distinction. He gave his son every advantage of travel and education. Fifteen years of the younger's productive life were spent at the court of Louis XIV, the rest in Holland. His researches won for him membership in the French Academy of Sciences and in the Royal Society of London. Like Boyle and Cavendish, he remained a bachelor.

Galileo discovered the principle of the pendulum. Huyghens applied it. He adapted the pendulum to control the motion in the movement of a clock. By means of what is called the "verge" he was able to impart to the pendulum on each swing a slight impulse, sufficient to maintain its motion. Clocks had been known before, but they were very crude affairs. Beginning with this invention of Huyghens in 1657, pendulum clocks have been so improved that it is asserted that one of the best of those of the present day will not vary in its rate of running more than two-hundredths of a second in a month. Professor W. I. Milham, an authority on clocks, says, "It will be seen that from 1360 when the first unquestioned mechanical clock was produced until 1658 there were practically no changes or improvements in clock mechanism. In less than one century following 1658 all these radical improvements were introduced and the clock became practically the clock of to-day. The last one hundred and fifty years have seen only minor changes, constantly improved workmanship, and a steady increase in the time-keeping accuracy.''

Huyghens worked out the law of the pendulum in mathematical form and showed how this instrument might be used to measure the varying acceleration of gravity from place to place over the surface of the earth. He, too invented the compound pendulum, and in this work he anticipated the discovery of the principle of the Conservation of Energy. Dr. Henry Crew in his *The Rise of Modern Physics* says: ''The problem of a freely falling body, solved by Galileo, is the first great solution in dynamics; that of the physical pendulum by Huyghens is the second and an immensely more difficult one. It was in fact the first dynamical system, as distinguished from a particle, to be studied It was too complex for Galileo; and it was a stumbling block to Descartes; but perplexity is the beginning of knowledge. Some of the most important concepts and principles of dynamics center about the pendulum.''*

The law of centrifugal force, which proved of such great assistance to Newton in his solution of the problems of planetary motion, was first worked out by Huyghens. In this development, he anticipated Newton in distinguishing between mass and weight, although he did not formulate the idea with the precision of his illustrious friend.

The well-known theory of a luminiferous ether of space, the hypothetical medium through which radiant energy is supposed to be transmitted, was the invention of Huyghens. Had he done nothing else, he would be entitled to enduring fame. Not until the revolutionary era of the present have aspersions been cast upon the good standing of this one-time logical necessity of scientific thinking. Indeed, it is even yet a long way from having lost the battle for existence. However, this utterly elusive medium of all space will be reserved for discussion in the next section together with Huyghens' equally epoch-making conception of the wave theory of light, a contribution to science which struggled long for recognition and which is only now beginning to suffer from partial eclipse.

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THE GROWTH OF A THEORY OF LIGHT

The sensation of light is one of the first of human experiences. We accept it as a matter of course. It seems almost absurd to inquire into its nature. Not for many centuries did it occur to any one to do so. The sun provided light as it did warmth. There was something about the moon and stars which made it possible to see them. Fire and flame also provided light. It was simply their nature to do so and entirely useless to speculate further about the matter.

The human mind does not long rest content with such a picture. If it has no legitimate explanation, it invents one. In the early days of ignorance and superstition, that the theory devised bore no relation to known facts mattered not the slightest. The early approaches to the solution of the problems of Nature did not lie along the avenue of facts. Facts were of little consequence. If an idea seemed plausible, it was accepted. The conception of critical analysis had not crossed the threshold of human understanding. The wild speculations of unbridled fancy were everywhere legal tender of the realm in the attempted explanations of natural phenomena.

Accordingly we find Plato and Aristotle contending that light is a property of the eye. They pictured the eye as sending out something in the nature of hypothetical tentacles which intercepted an object and so illuminated it. Just why these light-giving messengers of the eye should cause one object to be exceedingly bright and another to shine only faintly, they did not explain. In view of their childlike conceptions of Nature and her ways, the fact that there should be much light on a clear day and but little when the skies were cloudy seemed not to disturb their theory in the slightest. Many discoveries since, particularly the chemical changes taking place in a photographic plate, prove that light is a form of energy entirely independent of the eye in its origin. However, long before these discoveries were made, the crude theory of Plato and Aristotle was abandoned.

The first bit of information of a scientific sort regarding the nature of light came with a study of lenses. It was discovered that three-cornered pieces of glass—prisms we call them—are able to bend the rays of light passing through them. This property is called refraction. It is an important factor in the operation of the glasses which correct your faulty vision. In fact, one of the most remarkable of lenses is to be found in the human eye. Its ability to modify automatically its power of refraction for near and distant objects enables you without strain to view the panorama of Nature or the shifting scenes of human activity.

Just a word about this property of refraction. You have often observed the apparent bending of an oar at the water line or the misplacement of a line of type when looked at obliquely through a thick piece of plate glass. These effects are due to refraction. That is, rays of light in passing from a medium of one density to that of another density are bent. If the passage is to a transmitting material of greater density, the bending of the light ray is toward the perpendicular at the point of incidence, as the point where the ray enters the second medium is called. In the reverse case, the ray is bent away from the perpendicular erected at this point. Now in the case of the oar, the ray is passing from some point on the oar through the water and into the air on its route to your eye. As it leaves the water, the more dense medium, and enters the air, it is bent away from the perpendicular, or downward toward the water. You seem to see the point on the oar from which the ray comes, not in its true direction, but in the direction in which this ray enters the eye. The multitude of rays coming from all points of the oar are refracted in the same way and, therefore, the oar appears to be bent. For this same reason a clear pool of water seems to be shallower than it is.

Now this law of refraction had been worked out in advance of Newton's time, particularly by Snell, of the University of Leyden, and Descartes, of France. It was long known as Snell's Law. Ever since the time of Galileo it had been known that the image-producing properties of a lense depend upon this fact. However, great difficulties had been encountered in the practical use of telescope lenses. These difficulties seemed to be associated, too, with another property of light, namely, its apparent decomposition into the spectral colors. The rainbow had been an object of curiosity and wonder from the dawn of civilization. From the fourteenth century it had been regarded as a product of refraction of sunlight by raindrops, and Descartes had worked out the angles involved. However, he could not explain the colors.

This was the situation when Newton began his investigations in the field of optics. His immediate interest was a highly practical one. He wished to improve the image-producing qualities of lenses for telescope purposes. A troublesome color fringe appeared about the image. To reduce this to a minimum, it had been customary to grind lenses almost flat and of very great focal length. This necessitated a long and unwieldy telescope, awkward to manipulate and requiring a prodigious amount of time and patience in its use. Indeed, telescopes two hundred feet long and with no tube connecting object-glass and eyepiece were not unknown. It was with such an instrument that Huyghens discovered the true shape of Saturn's rings.

Newton began by calculating mathematically the proper curvatures of a lens. Then he proceeded to grind the lens as nearly like the theoretical figure as possible. Still, the images were blurred and indistinct. After a time, the thought occurred to him that the difficulty might lie in the nature of light itself. There was only one way to tell. He must experiment with light and analyze its properties. This, he proceeded to do, little knowing that he was embarking upon an investigation which was to engender one of the most protracted controversies in the history of physics.

To make a long story short, as the old saying goes, in a series of beautiful experiments, Newton analyzed sunlight into its constituent colors. He showed that white light is not simple, but compound. By passing sunlight through a triangular glass prism, he was able to disperse it into the colors of the rainbow—red, orange, yellow, green, blue, indigo and violet. By means of a second prism, placed in the reverse position, he brought about the recombination of these colors to form white light again. That is, he took advantage of the refractive properties of light to decompose it and then to put it together as it had been before the dispersion occurred.

In this work, by a prodigious amount of pains, Newton succeeded in screening out all but a certain color and then passing this, red for example, through another prism. One by one, he did this with the other colors, measuring in each instance the angle of refraction. The result was the fundamental discovery that the degree of refraction increases regularly from red to violet, the bending being greatest for violet and least for red.

No longer could color be regarded as a property of the object. The ancient ideas regarding this phenomenon of Nature forthwith went on the scrap heap. Leonardo da Vinci and his predecessors had been wrong. A red piece of cloth, for instance, does not alter the nature of the light reflected from it. A ray of light in passing through a transparent plate of blue glass is not dyed in the process. Newton's experiments made it clear that the cloth absorbs, in this case, all the colors from the light thrown upon it but red and reflects this, or at least red is the dominating color in the reflection. The blue glass is opaque to all colors but blue, transmitting only this.

Suppose you try the experiment of throwing in succession white light, red light and blue light upon the Stars and Stripes. This can easily be done in a dark room with an ordinary projection lantern for which you have transparent red and blue slides. As you hold the flag in the plain white light of the lantern with no slide in the holder, it appears in its natural colors. The white portion reflects all colors equally; the red stripes absorb all the colors but the red and reflect this; while the background for the field of stars does likewise for the blue. Now throw red light upon the screen. The white portions appear light red, the red stripes are an exceedingly deep red, but the blue background is black. The background receives nothing but red and is capable of reflecting only blue. Therefore, it reflects nothing and appears to be black, for black results from the absence of color. Then, follow the red slide with the blue one. Now the red stripes are black, the background an intense blue, and the white stripes a light blue.

Although Newton's experiments carried the world a long way forward in its understanding of the nature of color, nearly a century passed before it was discovered that white light produces only a very few sensations. This interesting fact was made known through the investigations of Dr. Thomas Young, one of the half-dozen outstanding leaders in developing a theory of light. His was a wonderful personality, being one of those prodigies who appear only occasionally in a century. The account of his childhood reads like a fairy-tale. While still an infant, it is said that he could read fluently. At four years, he had read the Bible through twice, and before he was ten he had shown a remarkable aptitude for languages. By the time he was fourteen he was a gifted linguist. More than this, he was equally proficient in a half-dozen other fields—music, literature, mathematics, science, philosophy and art. One biographer says of him, "He had the range of a mere dilettante, but everywhere the full grasp of the master." When only twenty he began to communicate papers to the Royal Society. Having studied medicine, he came to London in 1801 as a practising physician. Soon after he was prevailed upon to accept the professorship of natural philosophy in the newly established Royal Institution, where Davy was then professor of chemistry. There, he made his important contributions to the science of light.

Young distinguished between the physiological and the physical properties of light. He showed that light can produce in the eye only the three fundamental sensations of red, green and violet. He pointed out that blue, for instance, results from the addition of green and violet; the sensation of yellow arises from a combination of red and green; and that the various other shades of the spectrum are produced by other blendings of these three color sensations. That is, while sunlight consists of an infinite number of different colors, each possessing physical properties of its own, the sensation of color is largely a physiological phenomenon. The color is all in your eye. Of course, however, the objective stimulus exists.

This difference between the physical and the physiological aspects of light is illustrated by the fact that the pure yellow light of the sodium flame, for instance, can not be separated into red and green, as might be expected from their physiological combination to form this color. Likewise, the blue of the hydrogen flame can not be analyzed by the prism into green and violet. While the simultaneous sensations of these colors give the physiological effect of blue, spectral blue does not result from the physical composition of them.

The study of pigments, too, gave another slant to this phenomenon of color. Artists recognize the three primary colors—red, yellow and blue. As is well known, a mixture of yellow and blue pigments gives the effect of green. The color of a pigment is due to the character of the light it reflects. In the case of yellow, the predominant color is yellow, but there is also present in the reflection some unabsorbed green, masked by the yellow. The same is true of the blue pigment. The greater part of the reflection consists of blue, but there is present some unabsorbed green. When these two pigments are mixed, the yellow and blue, being complementary, neutralize each other to form white, while the unabsorbed green is left. The fact that yellow and blue are complementary can be shown by rapidly rotating two cardboard disks, one yellow and the other blue, so overlapped as to expose about equal portions of each color. The disk, then, appears to be solid white. The sensations of these two colors follow each other so rapidly upon the retina that one does not have time to disappear before the other takes its place. The physiological combination is white.

An interesting variation of the foregoing experiment and a less difficult one to perform consists in holding against a white background, say a screen illuminated by a projection lantern, a blue disk. If one gazes intently at this blue disk for a few seconds and it is then suddenly removed, a patch of yellow, the complementary color of blue, will appear to replace the disk. The continued exposure to blue has for the moment dulled somewhat the keenness of the optic nerve to the perception of this color. Consequently, when the disk is removed the complementary color, present in the white light on the screen, stands out. If a yellow disk is held against the screen and then removed, blue appears to replace it.

As we shall see, the distinction between the physiological and the physical properties of color was not Young's most important discovery regarding light. However, let us return for a moment to the outcome of Newton's experiments. When he had discovered the composition of white light, he recognized that the outer edge of a lens acts like a prism in separating the light passing through it into its component colors. Accordingly, he despaired of being able to overcome this defect sufficiently to make the refracting telescope a satisfactory instrument. Abandoning his pursuit in this direction, Newton in 1670 built the world's first reflector, the type which now seems destined to dominate in the field of future telescope construction. In passing, let it be said, that about three-quarters of a century later Chester More Hall and John Dolland, two English opticians, working independently of each other, did succeed in neutralizing the color dispersion of lenses. They ground the first achromatic lenses, and until recent years, the refracting telescope held the lead in the big observatories of the world.

THE NATURE OF LIGHT

Light, of course, is the absence of darkness. But, why should there be either light or darkness? What is the nature of this *something* which produces the physiological effects called light? What is the character of this form of energy which affects a photographic plate, tans the skin and produces chemical changes in the living cells of green leaves? Such questions have been asked ever since the time of Newton, and they have by no means been answered yet. We have seen what were the crude notions of Plato and Aristotle. And nothing further of importance was advanced until the coming of Newton and Huyghens in the seventeenth century. These two great pioneers in so many fields put forth rival theories which provoked a controversy lasting for a century and which is not yet entirely settled. Discoveries of the new physics have produced experimental facts which can not be reconciled with either theory alone, and no larger view capable of embracing both has yet appeared.

Let us consider first the conclusions at which Newton arrived. He was the author of the famous corpuscular theory. He believed that a luminous body emits minute particles at great speed. When these come in contact with the retina, they produce the sensation of sight. They were thought to be material particles of exceeding fineness, which spread in all directions and travel in straight lines. In passing through a transparent solid such as glass or through a liquid, it was supposed that these particles traveled in the spaces between the molecules.

By the exercise of Newtonian ingenuity it was found possible to explain all the phenomena of light known at that time on the basis of the corpuscular theory. To account for reflection was simple enough. These particles, like rubber balls, bounced away from the reflecting surface in such a direction as to make the angle of incidence equal to the angle of reflection. In the case of refraction, it was found necessary to assume that the velocity of light is greater in a dense medium such as glass than it is in a less dense one such as air. The bending of the rays could not be mathematically explained on the opposite supposition. At first thought, it seems absurd to believe that light should travel faster in a more dense medium. But Newton had no difficulty. Since these corpuscles of light were material particles, they were subject to the attraction of gravitation. Therefore, when light approaches a more dense medium, the increased attraction should hasten the speed of the particles. However, that a transparent medium such as glass should both reflect and refract light at the same time was exceedingly difficult to understand. Why should some particles be reflected, while others are attracted and enter the medium at increased speeds? For this, Newton had no satisfactory answer.

And there were other difficulties. For instance, it was not easy to see why these corpuscles should all have the same speeds, regardless of their source. Many of the stars are much larger than our sun. It would seem that the gravitational pull should often slow these corpuscles up or even stop them. Apparently, these differences in the masses of the stars had no effect. However, in the Einstein theory we shall find a very real echo of this aspect of the situation.

By observation of the moons of Jupiter, Roemer had, in 1675, determined the velocity of light to be approximately

186,000 miles a second. How could the delicate retina bear bombardment by material particles moving at that speed, be they ever so light? Dr. Paul Heyl says, ". . . it was known that if the light particles weighed as much as a millionth of a grain we could no more bear their impact than we could withstand a load of sand discharged point blank from the mouth of a cannon." It was recognized, too, that this ceaseless liberation of light particles should in time diminish the masses of the sun and stars, but there was no way of determining the rate. Singularly enough, we believe to-day that the radiant energy of these bodies is the product of the dissipation of their masses, although the method by which it is accomplished is totally different from that of the corpuscular theory.

Newton's theory evoked much criticism. Late in 1675, he wrote to Leibnitz, "I was so persecuted with discussions arising from the publication of my theory of light, that I blamed my own imprudence for parting with so substantial a blessing as my quiet, to run after a shadow."

Now let us consider the wave theory of Huyghens. Shortly after Roemer's announcement of the finite velocity of light, Huyghens read a remarkable paper before the French Academy, in which he showed that most of the phenomena of light, including its velocity, could be quite simply explained in terms of wave movement in a luminiferous ether filling all space. Each luminous particle taken as a source was pictured as communicating pulses or waves to the surrounding ether, much as a pebble thrown into a pool communicates waves to the water through which it passes.

Fresnel, one of the most brilliant exponents of the theory at a later date, stated it as follows: *"The vibrations at each point in the wave front may be considered as the sum of the elementary motions which at any one instant are sent to that point from all parts of this same wave in any one of its previous positions, each of these parts acting independently the one of the other."*

The controversy was now on. Although it is commonly supposed that Newton rejected the wave theory, this is not altogether true. He saw difficulties in its complete acceptance and did not become a supporter of it. However, he argued against it with reluctance, and in his explanation of the colors of thin plates he combined in a peculiar fashion the wave and corpuscular theories. Still, because of his great prestige, Newton's failure to endorse the view of Huyghens was beyond question a big factor in its delayed acceptance.

One of Newton's chief objections to the wave theory was his belief that it could not account for the straight-line propagation of light. Light was known to travel in straight lines. The clear-cut, definite outlines of shadows cast by objects standing in the pathway of light coming from a short narrow source indicated this. The pinhole camera also affords a beautiful illustration. In a darkened room, pierce the shutter with a fine instrument, say a sewing needle. Then, on a day when the light is good outside, hold a large white cardboard a few inches behind the opening. An inverted image of the landscape or of whatever the scene may be will appear on the cardboard screen. As can readily be shown by taking lines representing rays of light coming respectively from the top and bottom of some object in the scene, say a flag-pole, through the opening in the shutter to the image, the light must travel in straight lines. These and similar experiments seemed to prove that light does not bend around corners and obstacles, as sound does. That is, to use the technical term, light did not seem to undergo what is called diffraction.

To illustrate what is meant by diffraction, suppose we consider sound. Sound is known to be due to a wave movement in a material medium. We have already seen that one of the early experiments with the air-pump was to show that sound will not travel in a vacuum. Let us state at this point, too, that sound waves are longitudinal in form. This means that the particles of the vibrating medium—gas, liquid or solid—undergo alternate compression and rarefaction in the direction in which the sound is traveling, which of course is outward in all directions from the center of disturbance. If you could view a single particle during the passage of a train of sound waves, you would observe that it executes a rapid to and fro motion. In the absence of any particles to vibrate, as in a vacuum, there can be no sound.

It is a matter of common experience that sound waves are diffracted. The longer the waves, that is, the lower the pitch, the more easily this occurs. Probably many of you at some time or other have happened to stand on a cross street at some distance from a street on which a band was marching. If so, you doubtless noticed the change in the quality of the music as the band came into view. While it was around the corner, the low notes, those of longer wave length, were louder and more prominent. However, as the band came to the cross street the notes of higher pitch, those of shorter wave length, became much more noticeable. This is because the longer waves coming from the bass instruments are more skilful in shooting around corners. That is, they are more easily diffracted.

To the early observers, light seemed to exhibit no signs of diffraction. It traveled in perfectly straight lines. If one were not on the main thoroughfare, he did not see the procession go by. All wave movements known underwent diffraction. If light did not, then it could not consist of waves. Here, the corpuscular theory had the advantage. At least, for a time. Then the advantage disappeared, for it was shown that light can be diffracted. Grimaldi, a Jesuit professor of mathematics at Bologna, who died while Newton was still a student at Cambridge, had shown this before either the corpuscular or wave theory was advanced. However, this discovery had been overlooked, and it remained for Young and others at a later time to make it again. For instance, if a bright source of light is placed behind a narrow slit and five or six feet in front of this a fine straight wire is held parallel to the slit, an interesting sort of shadow will be cast on a screen, which should be placed about ten feet beyond the position of the wire. An inspection shows that enough light bends around the wire to illuminate the center of the shadow. In addition, there will be seen a number of bright and dark bands parallel to the shadow of the wire. These are due to a combination of the effects of diffraction and interference, to be discussed presently.

The foregoing and other experiments proved that light does not always travel in straight lines. However, we have seen that the shorter wave lengths of sound undergo this bending much less readily than do the longer ones. Light waves, if they existed, were known to be inconceivably short in comparison with sound waves. Thus, the detection of their diffraction was the more difficult. However, when it was discovered, this property became a powerful support to the wave theory. The corpuscular theory could not so readily account for this fact.

Let us come now to the subject of interference, mentioned above. The discovery of this property as it applies to light was made by that early nineteenth-century genius, Thomas Young, who, as we have seen, did so much to clarify the subject of color. The meaning of interference is of course clear enough. Interference in one form or another is responsible for a deal of friction in human affairs. Discord, we call it in music. In any case, it destroys something—happiness, musical harmony or light.

Suppose you start to walk down the street with another person. You take sixty steps in a minute, and he takes sixty-one. At the beginning, you are in step, and at the end of a minute you are in step. But in the middle of the minute, you are in direct opposite step. From the first you began to get more and more out of step until at the mid-point this interference had reached a maximum. Then you began to get more and more in step until at the end of the interval you were stepping in unison again. Interference here produced an awkward situation. In sound, it produces silence and in light darkness.

Again, suppose we sound two tuning-forks, preferably mounted on resonator boxes to intensify the volume. Let us assume, too, that one of these forks makes two hundred and fifty-six vibrations, or waves, in a second, while the other makes two hundred and fifty-five. At the beginning of the second, these forks are in step. They are vibrating in unison so that the waves reinforce each other and increase the volume of sound. However, just as in the case where you and your friend are walking down the street, at the middle of the second they are in direct opposite step. The waves from one fork neutralize the effect of those from the other. The result is silence. At the end of the second, the forks are again in unison. This alternate reinforcement and interference of sound waves gives rise to the phenomenon of what is known as beats. If the difference in the vibration numbers of the two forks is two instead of one, the number of beats per second will be two, and so on.

That it should be possible for light to produce darkness was a surprising discovery. If we turn on two electric bulbs in a room we expect the illumination of the room to be increased. Young contrived an experiment to show that two lights may be made to give not more, but much less illumination than one light alone. This was more than a hundred years after Newton and Huyghens had put forth their rival theories and at a time when the wave, or undulatory theory, was languishing somewhat.

In a thin piece of cardboard, Young made two fine pinholes very close together. Through these openings, he viewed a small and rather distant source of light. To-day a bright street lamp would be a suitable source. By holding this screen close to the eye, he beheld a series of bright and dark parallel bands. Viewing the distant source of light through either pinhole alone gave a continuous field of bright light, without any bands. Clearly, the light rays coming through the two separate openings reacted upon each other in some way. In the region of the dark bands, the light from one pinhole appeared to be destroyed by the light from the other. That is, interference seemed to have occurred. Let us give the explanation in Young's own words:

> "It was in May, 1801, that I discovered, by reflecting on the beautiful experiments of Newton, a law which appears to me to account for a greater variety of interesting phenomena than any other optical principle that has yet been made known. I shall endeavor to explain this law by a comparison.
>
> "Suppose a number of equal waves of water to move upon the surface of a stagnant lake, with a certain constant velocity, and to enter a narrow channel leading out of the lake. Suppose then another similar cause to have excited another series of waves, which arrive at the same channel, with the same velocity, and at the same time with the first. Neither series of waves will destroy the other, but their effects will be combined: if they enter the channel in such a manner that the elevations of one series coincide with those of the other, they must together produce a series of greater joint elevations; but if the elevations of one series are so situated as to correspond to the depressions of the other, they must exactly fill up those depressions, and the surface of the water must remain smooth; at least I can discover no alternative, either from theory or from experiment.
>
> "Now I maintain that similar effects take place whenever two portions of light are thus mixed; and this I call the general law of the interference of light."

The elevations and depressions of which Young speaks are the crests and troughs. His explanation is wonderfully lucid. If light is a wave movement, each wave consisting of disturbances corresponding to the crests and troughs of water waves, or to the condensations and rarefactions of sound waves, then the union of two sets of such waves should be able to produce precisely the sort of bright and dark bands which Young had observed. This was a great victory for the adherents to the wave theory. The combination of two streams of rapidly moving corpuscles seemed in no way to be able to account for this experimental fact.

You have often noticed the colors which appear when a few drops of oil spread out on a wet pavement or those in a thin soap film, and you have seen the brilliant hues of peacock feathers and the coloration of mother-of-pearl. These are the results of interference of light waves reflected from the surfaces of thin transparent films. When it was shown, too, that light in passing through a diffraction grating, a piece of glass upon which from fifteen to twenty thousand fine lines to the inch have been ruled, gives rise, through a combination of diffraction and interference, to spectra, the wave theory seemed to have won the battle.

Another brilliant worker now came to the support of the wave theory, for despite the great successes won, it still had opponents. This man was a young French engineer, Augustin Fresnel, who, fifteen years after the investigations of Young and without knowledge of them, devised and carried out a series of searching experiments, which gave to the world the wave theory of light practically as it is known to-day. Fresnel cleared up certain difficulties left by Young, but most important of all he showed the conditions under which polarized light will interfere, and thereby arrived at the important conclusion that light waves are transverse, like water waves, and not longitudinal, like sound waves, as had been theretofore supposed.

And now we must know what polarized light is. Certain crystals, such as tourmalin, for instance, have the property of permitting light to pass through them in only one plane. So long as you have only one crystal, this property can not be discovered, for in any way you may hold it the light will pass through. However, with two such crystals the effect at once becomes apparent. Suppose you place these crystals one upon the other and then hold them in front of the eye. Let us say that light passes through both of them in these positions. Now slowly rotate one of the crystals through an angle of ninety degrees. Gradually the light is cut off until, when the position at right angles is reached, no light at all passes through.

These crystals polarize light. That is, each transmits light in only one plane. At the beginning of the above experiment, these planes of the two crystals were in the same relative positions with respect to each other. The light having passed through one could pass without hindrance on through the second. But when one of the crystals had been rotated through ninety degrees, its plane of transmission was directly across that of the other crystal. In other words, it blocked the passage of the light.

Important conclusions were drawn from this demonstration. In the first place, it seemed to offer additional objection to the corpuscular theory. If light consisted of infinitesimally small particles moving in straight lines, there seemed to be no reason why they should not move in one plane as well as in another, regardless of the structure of the medium. And then again, if light is a wave movement, this experiment seemed to show that it could not be a longitudinal movement, in which the vibrating particles move to and fro in the same direction in which the wave form travels. Rotating one of the crystals could not interfere with such a movement.

If light waves were thought of as transverse, this phenomenon of polarization found a ready explanation. In transverse waves, the vibrating particles move to and fro at right angles to the direction in which the wave train is traveling. To get the idea, attach a rope to a hook in the wall and by the movement of the hand at the other end shake it into a series of waves. The wave movement is up and down, while the form of the wave travels forward. Now, if light waves are of this form, it will be seen that turning one crystal through an angle of ninety degrees interposes a barrier to the continued execution of this wave movement. You will get the idea if you imagine vertical slats set in two wooden frames, similar to window frames. As long as these two sets of slats are in the same relative positions with respect to each other, you could pass your rope through them and throw it into a set of transverse waves. However, place one frame at right angles to the other and the transverse movement is stopped. Just so with light waves. It was thenceforth seen that they must be transverse.

All along the line, the wave theory of Huyghens seemed to have won over the corpuscular conception of Newton. However, apparently the death blow came to the latter when in 1853 Foucault performed an experiment which proved that light travels more slowly in a dense medium, such as water, than it does in a light one, such as air. This discovery made it no longer possible to explain refraction on the basis of the corpuscular theory. On the contrary, the wave theory demanded for its satisfaction the condition shown by the Foucault experiment.

Were it not for the experimental evidence for light quanta, produced during the present century and to be discussed in a later chapter, we should write finis across this historic controversy. In any case, the revived conception of some sort of corpuscular theory is quite different from that of Newton. As we shall see, both the wave theory and the quantum theory seem indispensable in accounting for certain diverse facts of experimental research. Here on the frontier of the physical world an as yet unbridgeable gulf appears to have been reached.

THE THEORY OF THE ETHER

The theory of an ether, yes, of a whole family of ethers, for the explanation of all sorts of mysterious natural phenomena, is almost as old as scientific speculation itself. However, the real ether theory which has figured so largely in the development of modern physics dates from Huyghens. True, Newton had indulged in vague notions of an ether, both in connection with his corpuscular theory of light and to account for the force of gravity. Of the latter function, he says: "For this end I will suppose ether to consist of parts differing from one another in subtility by definite degrees; that in the pores of bodies there is less of the grosser ether, in proportion to the finer, than in the regions of the air; and that yet the grosser ether in the air affects the upper regions of the earth, and the finer ether in the earth the lower regions of the air, in such manner, that from the top of the air to the surface of the earth, and again from the surface of the earth to the centre thereof, the earth is insensibly finer and finer. Imagine now any body suspended in the air or lying on the earth, and the ether being by the hypothesis grosser in the pores, which are in the upper parts of the body, than in those which are in its lower parts, and that grosser ether being less apt to be lodged in those pores than the finer ether below, it will endeavour to get out and give way to the finer ether below, which cannot be, without the bodies descending to make room above for it to go out into."

Certainly, Newton was not happy in this wholly imaginary hypothesis. However, he did not stress it. The ether was not an important factor in Newton's system. In his official capacity, he did not profess to account in any thoroughgoing way for gravitation. He observed its behavior, formulated the equations governing it and accepted it as an unsearchable fact of Nature. He did in a rather vague way evoke an ether to assist in the reconciliation of the apparent contradiction involved in the simultaneous reflection and refraction of light in a transparent medium. But this was all.

With Huyghens, the situation was different. It seemed manifestly impossible that radiant energy should be able to travel through interstellar space in the form of waves without something in which to travel. There must be some sort of a medium to be thrown into a wave movement. This appeared to be a logical necessity. And so Huyghens invented an ether. From that day to this, the only justification for it has been this inherent necessity of human thought. Having abandoned the corpuscular theory of Newton, it was simply unthinkable that heat and light can travel from the distant stars without some medium of transmission.

But what is the ether? It does not respond to any of the senses. Intangible, elusive, utterly beyond the reach of human intuition, its properties have been those which the tasks imposed upon it seemed to demand. And it has been a patient servant. Whenever a new phenomenon has come along which appeared to require some special means of accomplishment, the burden has been thrust upon the uncomplaining ether. An ether having all sorts of apparently necessary characteristics has from time to time come to the fore. "Working models" have been constructed to explain its operation. Mathematicians seemed to develop these "for the love of it." Often quite contradictory physical properties have been assigned to the ether. For instance, it has been imagined as an ethereal fluid, too fine and imponderable for physical manifestation, but more often as an elastic solid. More and more its extraordinary nature, different from anything with which men are familiar in their laboratories, became apparent. Experiments to detect its existence have failed utterly. Finally, with the coming of Maxwell, the ether ceased to be mechanical in character and became electromagnetic, a transformation which will be discussed in its proper place.

Let us look at some of the difficulties encountered in the evolution of the ether theory. In the first place, Huyghens assumed that the ether waves were mechanical vibrations of the longitudinal type, as in sound. Such an ether at once failed to account for polarization of light and the production of colors. Fresnel nearly a century and a half later, as we have seen, showed that the form of the waves must be transverse. The opponents of the theory would not admit that transverse vibrations were possible in a fluid medium such as the ether was assumed to be. To this, Fresnel replied that the ether behaves as though it were an elastic solid. Then, it was asked why, if all space were filled with an elastic solid, does not this solid impede the movements of the planets and other heavenly bodies? Furthermore, the properties of such a solid remained vague and indefinite. No clear conception was forthcoming. The fact was and is that no one had had any real experience with this hypothetical ether. The phenomenon of interference presented still another difficulty. If light were a real substance, how could any combination of it equal nothing?

Men were groping for the truth and challenging in the true spirit of scientific inquiry every hypothesis put forward. In time they were bound to arrive at a conception more in accord with the facts of experimental work. That happy state has partially arrived, but we are by no means yet out of the woods. Just now we are torn between the logical necessity of assuming some sort of medium for the transmission of radiant energy and the baffling fact that there appears to be no possibility of demonstrating its existence. Einstein is getting along very well without an ether.

THE VELOCITY OF LIGHT

For centuries, light was believed to travel with instantaneous speed. Galileo, that first great inquirer into Nature's secrets, made an attempt to measure its velocity. With observers on either of two hills twenty miles apart, he flashed signal lights between the two. He did not realize the stupendous problem he had set himself, and of course his conclusions did not modify the traditional belief.

The first tangible evidence that light does take time to travel came from observation of the eclipses of the moons of Jupiter. The precise interval between two successive passages of one of these moons into Jupiter's shadow could be determined with great accuracy. It was then a simple matter of calculation to predict the times of future eclipses. However, as the earth moved in its orbit from the position between the sun and Jupiter to the far position on the opposite side of its orbit six months later, these eclipses kept coming later and later, until, when the extreme position was reached, they were occurring about 1000 seconds behind schedule. When the earth had returned to the near side with reference to Jupiter, the eclipses were again on schedule time. At first a puzzle, it was soon concluded that the discrepancies between the theoretical and the actual times of these eclipses were due to the time required for light to pass across the constantly increasing space separating the earth and Jupiter. The maximum of this additional distance was the diameter of the earth's orbit, known to be 186,000,000 miles, and the maximum delay in the appearance of the eclipse, as stated above, about 1000 seconds. This showed that the velocity of light is about 186,000 miles a second. Roemer, in 1676, made this determination.

Bradley, an Englishman, devised another astronomical method for finding the velocity of light, while Foucault, of Paris, succeeded in 1853 in measuring the relative speeds of light in air and water, finding it less in the more dense medium. This was the crucial test which turned the tide of battle against the corpuscular theory. Professor A. A. Michelson, of the University of Chicago, has made the most accurate determinations, his most recent result giving 186,300 miles.

As we shall see, the velocity of light is a quantity of much significance in the Einstein theory. The sunbeam has become the measuring rod of the universe. Should the light on the nearest fixed star go out to-night, it would still shine on in the heavens with the same brilliancy for four and a third years, so long would the last light messenger be in reaching us from that comparatively near-by sun. Suppose a bird were flying with the velocity of light and a marksman were skilful enough to shoot him on the wing. If the bird were sixteen feet above the ground, the distance a body under the influence of gravity falls in the first second, the bird would pass seven and a half times around the earth at the equator before striking the earth, and the marksman would have to travel half-way around the earth to pick up his game. Again, suppose you had been on the pole-star with a telescope powerful enough to view events here on the earth and that you had been trying to witness the battle of Gettysburg, fought in July, 1863, so slowly do the light waves bearing the impress of the scenes travel that you would not have been able to see them until January, 1905. A new star suddenly blazes forth, but it may be that the celestial conflagration giving rise to it occurred several centuries ago. The view of the heavens which we obtain to-night represents scenes, many of which are hoary with age. It is estimated that it would require a light ray three thousand centuries to pass from side to side across our own galaxy of stars.

It seems, for reasons which will appear later, that the velocity of light is the greatest possible velocity to obtain anywhere in this universe. A certain imaginative French writer pictured a group of workmen engaged in planting charges of dynamite in holes drilled in rocks. Of a sudden this dynamite exploded, tearing away the fragment of the earth's crust upon which these men happened to be located. Furthermore, this bit of earth and rock began speeding through space with a velocity greater than that of light. Presently, these men sitting upon this sliver of matter overtook the preceding light waves bearing to outermost space the picture of their catastrophe, thus enabling them to look back and see themselves busily at work planting the charge of dynamite which had worked their ruin.

At a later point, we shall see that light possesses inertia and exerts a pressure. That it is a form of energy, a multitude of experiments prove. However, its true inwardness remains to be discovered.

We have now seen the science of physics grow from a toddling infant to a position of majesty and power. Its laws enfold the universe and dominate the ways of stars and men. The Newtonian epoch is typified by the vigor of youth. "There were giants in those days," and their persistent knocking at the door of eternal truth unlocked in some small measure the secrets which lay beyond. Again these pioneers were like great artists who sketched in outline a wonderful masterpiece, leaving the details to be filled in by their successors. They worked better than they knew. Without the beginnings which they made in many diverse fields, the revolutionary discoveries of the present would still be in the future.

CHAPTER IV

Heat, or the Dance of the Molecules

HEAT AND HUMAN PROGRESS—NATURE OF HEAT—THE IMPONDERABLE CALLED CALORIC—DISCOVERIES OF BLACK—LATENT HEAT—HEATS OF FUSION AND VAPORIZATION—MEANING OF BOILING-POINT—SPECIFIC HEAT—DISCOVERIES OF DAVY AND RUMFORD—KINETIC THEORY OF HEAT—ATOMS AND MOLECULES—ILLUSTRATIONS—BROWNIAN MOVEMENT—EVIDENCE FROM COLLOIDAL SOLUTIONS — FACT AND THEORY — ILLUSTRATIONS — KINSHIP OF HEAT AND LIGHT—PUTTING THE MOLECULES TO WORK—RELATIONSHIP BETWEEN HEAT AND WORK—PERPETUAL MOTION—CARNOT AND MECHANICAL EQUIVALENT OF HEAT—FRIEDRICH MOHR—MAYER AND THE LAW OF THE CONSERVATION OF ENERGY—DEMONSTRATIONS BY JOULE—PAPER BY HELMHOLTZ—SECOND LAW OF THERMODYNAMICS—INTERPRETATION—DEGRADATION OF ENERGY—UNIVERSE RUNNING DOWN—MATTER AND ENERGY.

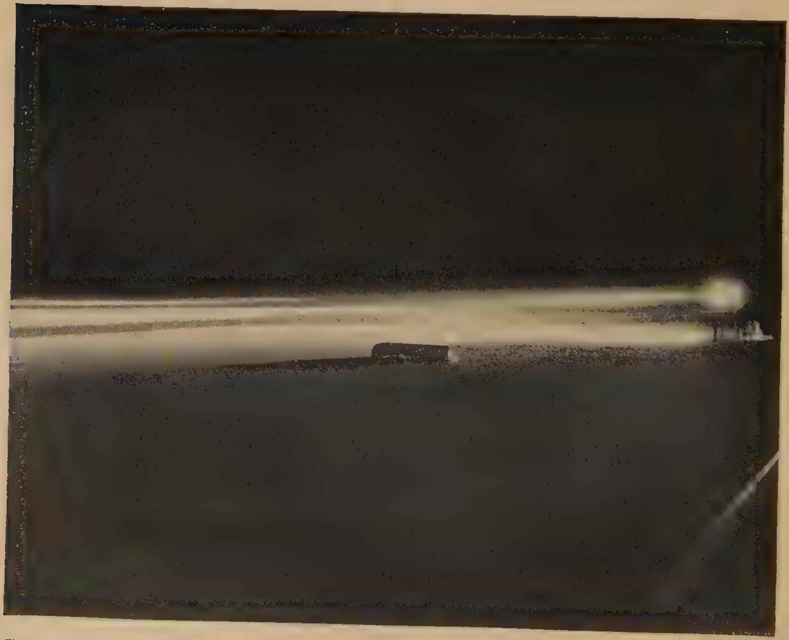
The idea of heat is synonymous with much in the progress of mankind. Instinctively, it carries us backward to the mastery of fire, the first great turning-point in the evolution of the race. For countless centuries before that strategic moment, the volcanic eruption and the lightning flash had arrested the attention of primitive men and preyed upon their fears. Then came a day when certain of them began to take note of the occasional kindling of fires by the chance rubbing together of two dry branches in a strong wind. It, too, must have been a matter of common experience that friction produces heat. Although long periods passed in which the use of fire extended only to a knowledge of the means of feeding and perpetuating it, there came a time when some one deliberately sought to create fire. With its accomplishment began man's first real mastery of Nature. The camp-fire before the open cave lured wild animals within his range. Over it, he learned to cook his food, and

Courtesy, General Electric Company

The *Saratoga:* a modern application of Archimedes' Principle

Courtesy, The Sperry Gyroscope Company

Using the gyro-compass—a marvelous application of Newton's Laws of Motion



Corpuscles or waves, light is very real. Scene on beach at Atlantic City during Light's Golden Jubilee celebration before its genial glow he basked in winter. In the dry air rising from its embers, he seasoned and toughened the wood which he shaped into formidable instruments of warfare. As the centuries passed and the knowledge of fire grew, those early gropers after a better mode of living slowly came into possession of the arts of pottery, glass-making and the metallurgy of the simple ores.

Probably there is not an article of industry and commerce which has not, directly or indirectly, come under the influence of heat. Examples might be multiplied to indefinite length. With each succeeding conquest in the mastery of high temperatures, the world's proficiency in the arts and industries has grown. We need only recall the oxyhydrogen blowpipe, the electric furnace, the acetylene torch and now the flames of atomic hydrogen. Heat is a chief basis of physical comfort. It is the motive power of material civilization. Were our sources of heat to vanish, this earth would automatically become a cold, dead, dreary world—the fossilized scene of an extinct manifestation of life.

The shifting centers of heat and cold have in times past exerted a tremendous influence in shaping the course of human evolution. The bitter cold of the glacial epochs was a big factor in the survival of the fittest. To-day the difference in intellectual vigor noted between the tropics and the temperate climes is largely due to inequalities in the distribution of heat. Heat, too, has figured in song and story. The genial warmth of the open hearth or the cottage fire has been a factor in the setting of many a tale. And when men came to imagine a place of eternal torment, they could picture no more appropriate emblem than a lake of perpetual fire.

THE NATURE OF HEAT

From the standpoint of physics, the nature of heat is a fundamental consideration. For long periods in the early history of men, no one gave it a thought. Like light, heat was accepted as a matter of course. It was a fact of Nature, and needed no explanation. Although fire was one of Aristotle's four elements, it is doubtful whether he ever formulated any ideas regarding its nature. The Greeks held heat to be a substance.

Not until the seventeenth century did men come to think of heat in a scientific way. In that golden age of pioneering, such leaders as Boyle and Newton looked upon heat as a form of motion. Believing as they did in some sort of ultimate division of matter into infinitesimally small units, they assumed that heat set these particles into vibration. Without knowing and without much evidence upon which to base their position, they anticipated a view of Nature which has come to be orthodox since the middle of the last century.

The eighteenth century with its extreme materialistic tendencies, however, saw a reversion to the crude ideas of prescientific days. That was preeminently the century of "imponderables." All sorts of hidden phenomena were explained by the aid of very subtle and attenuated forms of matter, too elusive and intangible to be capable of being weighed. There were at least a half-dozen such. Three imponderable fluids were required for the understanding of electricity and magnetism. Descartes, Huyghens, Hooke and Newton had postulated ethers of various sorts. Phlogiston was a famous substance of hypothetical origin, responsible for the process of combustion. That it was regarded as imponderable, however, is doubtful. Finally, caloric, the stuff called heat, was the oldest of all. It dates from Greek and Roman times, although Lavoisier, in 1789, coined the name. It seems an inharmonious circumstance that this gifted Frenchman, who overthrew with his well-planned experiments and keen analysis the false phlogiston theory and, as well, provided the experimental basis for the Law of the Conservation of Matter, should not also have seen the fallacy involved in identifying heat with material substantiality. But the fact is that Lavoisier accepted the view of his contemporaries and predecessors. In his *Elements of Chemistry*, he even included caloric among the chemical elements, along with carbon, nitrogen, oxygen, hydrogen and others.

Like light, heat was supposed to consist of corpuscles, highly elastic and mutually repelling one another, but attracted by ordinary matter. That some bodies should absorb heat more readily or in larger quantities than others was ascribed to their greater powers of attraction. Thus arose the expression "capacity for heat." It was perfectly clear to eighteenth-century scientists, and indeed to those in the first half of the nineteenth, that the temperature of a body rose because it had taken on more caloric. Expansion was easily explained by the pushing farther apart of the particles of the substance by the caloric corpuscles. The fact, however, that water reaches its greatest density at four degrees Centigrade and expands upon freezing, instead of contracting, could not be easily accounted for. When it was discovered that a sheet of plate-glass would prevent the passage of heat, although permitting light to pass, it was assumed that the corpuscles of these two imponderables were not the same. That friction should produce heat was explained by saying that the substance already contained caloric and the friction rubbed it out. However, this was an evident contradiction of the theory.

The first man to do any work of a real scientific nature on the subject of heat was the Scottish chemist, Joseph Black, of Glasgow (1728-1799), a contemporary of Sir Henry Cavendish and one of the most notable pioneers of the new-born science of modern chemistry. He made a remarkable observation. Apparently for the first time in the history of science, he took note of the fact that when ice melts it takes up a certain quantity of heat without undergoing any change in temperature. Of course, every one has noticed that, when ice is placed in a pitcher of water, the temperature quickly falls to approximately the freezing-point and remains there as long as there is any ice left in the pitcher. The ice is all the while absorbing heat in the process of melting, but neither the water originally in the pitcher nor that coming from the ice rises in temperature. Furthermore, it was discovered that even if the container is placed over a source of heat the temperature close to the ice remains stationary. Put in another way: if a pound of ice at 0 degrees Centigrade is mixed with a pound of water at 80 degrees Centigrade, the result will be two pounds of water at 0 degrees Centigrade. The heat given off by the water is entirely absorbed in changing the ice to the liquid state.

This was an amazing discovery. Black, in harmony with the imaginative theory of heat prevailing in his time, assumed that the imponderable caloric combined with the ice, thus becoming latent in the water. Here was the origin of the expression *latent heat.* In his *Lectures,* Black says, "Considered as the cause of warmth we do not perceive its presence; it is concealed or latent, and I gave it the name of *latent heat.*" Black also devised an ice calorimeter, a piece of apparatus for the measurement of heat transfers, and proved that to melt a pound of ice requires that an equal mass of water be cooled through 140 degrees Fahrenheit, which agrees very well with more accurate determinations. Here was a natural unit of heat, independent of any artificial value. It was what might be called a constant of Nature, and its discovery marked a turning-point in the progress of the physics of heat.

Although it is not clear whether Black drew the inference regarding the converse of this proposition or not, it was perfectly logical to assume that, when water freezes, it gives off a quantity of heat equal to that absorbed in the process of melting. We do not often think of freezing as a heating process, and yet it is. That is, a pond of freezing water is in the nature of a stove, by which one might with perfect propriety sit down to get warm. Not only does the Conservation of Energy, to which we shall come soon, require this, but a little reflection will show that we have practical experience of this phenomenon. A snow-storm is usually accompanied by a rise in temperature. That is, the freezing of large quantities of water vapor to form snow

Courtesy, General Electric Company

The jagged paths of electrons

Courtesy, General Electric Company

Electricity conquers the mountains

liberates heat, which warms the atmosphere. As we shall see, another factor enters into this as well, the latent heat of vaporization.

This idea of the latent heat of vaporization was also a discovery of Black. You know that, when water in an open kettle reaches the boiling-point, the temperature rises no higher. An equilibrium seems to have been struck. True, heat continues to be absorbed by the water, but it is all consumed in changing the water from the liquid to the vapor state. No matter how hot the fire may be made, the temperature will not rise above that of the boiling-point. Heat accumulates in the water until this point is reached. Then, the pent-up heat manifests itself in the process of boiling and this change of state seems to serve as a sort of safety valve. Black discovered that in this vaporization of water a large quantity of heat is absorbed just to produce the change of state. Although his figure was not accurate, we now know that it requires five hundred and thirty-six times as much heat to change a pound of water into steam at the normal boiling-point as it does to raise the same quantity of water through one degree Centigrade. Here was another natural unit of heat. Still, Black was laboring under the assumption that all of these phenomena of heat were due either to the absorption or to the liberation, as the case might be, of a subtle and mysterious substance called caloric.

Now, just as vaporization requires heat, so does the condensation of vapor to form water give off heat. Any one who has burned himself with live steam knows this. Furthermore, a pound of steam at the boiling-point condenses to water at the same temperature and in so doing liberates the same quantity of heat as would be absorbed in the reverse process. That accounts for the heating effects of a steam radiator. The water leaving the radiator is the same in temperature as that of the steam entering it, and yet a large quantity of heat has been liberated to the room. This is the latent heat of vaporization, first observed in a scientific way by Black. It must be clear now that boiling is a cooling process and that the reverse is one of heating.

A few moments ago, the "normal" boiling-point was mentioned. You who live at elevations above sea-level know that the boiling-point of water is not 212 degrees Fahrenheit or 100 degrees Centigrade in your localities. It is something less, depending upon the elevation. On Pike's Peak, water in an open kettle will boil away without getting hot enough to cook vegetables. For that reason, pressure-cookers must be used there. Housewives, too, know that such a cooker by confining the steam and increasing the pressure on the surface of the liquid increases the intensity of the heat and raises the temperature of the boiling-point. We also know that in the boiler of a steam-engine the steam pressure raises the boiling-point. Evidently, this point is in some way related to pressure. The boiling-point of a liquid in an open kettle is defined as the temperature at which the vapor pressure is equal to the atmospheric pressure. At sea-level with a normal barometer, the boiling-point of water is as given above. With increase in altitude and a falling barometer the boiling-point also falls, because the degree of heat necessary to overcome the air pressure is not so great.

In a vacuum, water boils almost down to the freezing-point. I once had a machine for freezing water by boiling it. A bottle containing water to a depth of about an inch was connected to an air-pump. As the air was exhausted, the water began to boil, the vapor being pumped over sulfuric acid in an intermediate chamber, which absorbed it. By removing the air pressure, the water reached its boiling-point. The heat for the boiling came from the water itself, and therefore the temperature constantly fell, getting closer and closer to the freezing-point. At length, the boiling ceased, and presently the water froze. The freezing, too, was instantaneous. It reminded me of the story of a farmer who averred that the temperature changed so suddenly one night as to catch in the frozen ice of his pond the frogs whose heads had been peeping through the water. Had I been able to measure it, I should have found heat being given off at the instant the water in my bottle froze.

We are all familiar with the practical application of a lowered boiling-point with diminished pressure in the refining of sugar. In the vacuum pans, the syrup is evaporated at low pressure in order to prevent burning.

Let us return for a moment to that point regarding the snow-storm. Not only is the atmosphere warmed by the act of freezing. The condensation of the water vapor also liberates heat. In the formation of either snow or frost, condensation and freezing occur together.

Even before the time of Black another important discovery regarding heat quantities had been made. You know that a piece of bright metal exposed to the sun's rays on a midsummer's day will become so hot that it will be decidedly uncomfortable to the touch. At the same time, water will become warm, but not hot. This and similar observations led to a knowledge of what is called *specific heat*. It means the quantity of heat necessary to raise a definite weight of a substance one degree as compared with the quantity necessary to raise the same amount of water one degree. The specific heat of water is high. For instance, it requires about thirty times as much heat to raise a pound of water one degree as it does to increase the temperature of a pound of mercury the same amount.

In passing, let us note that these heat properties of water exercise a wonderful influence in moderating climate. A place located near a large body of water does not suffer from extremes of temperature. In the spring, the water heats slowly, and in the autumn it cools slowly. The temperature of the adjacent land follows fairly closely that of the water. Furthermore, the water acts as an immense reservoir of heat, whose beneficent influence is spread far and wide. If the body of water freezes in winter, the large quantity of heat required in spring merely for the melting of the ice retards the coming of warm and balmy days.

CALORIC FACES A CRISIS

Two of the most picturesque figures in the pioneer period of modern science worked the undoing of caloric. A purely imaginative creation, this hypothetical substance could not endure the light of experimental facts. The two men whose discoveries thrust it from its pedestal were Count Rumford and Sir Humphry Davy. Let us begin with Rumford.

The title of this many-sided man of fame and fortune would indicate that his birthplace was abroad. However, it was at North Woburn, Massachusetts, and his name was Benjamin Thompson. Falsely accused of Tory sympathies early in the American Revolution, as a young man of twenty-one he decided to go abroad. There, he became secretary and personal friend of Lord George Germaine. His spare time was spent in scientific research, and he was elected a member of the Royal Society. Leaving England for the Continent, his rare charm and distinguished bearing won him the friendship of the Elector of Bavaria, who made him Colonel of Cavalry and placed at his disposal a palatial residence. Just previous to this, the King of England had knighted him. At thirty-five, he was made Major-General and Privy Councilor of State, and three years later a Count of the Holy Roman Empire. He then selected the name Rumford, after his early home in America. Upon his return to London in 1795, he was welcomed by the most learned and distinguished men of Great Britain. A little later, he founded there the Royal Institution for Scientific Research, a place which has been immortalized by the discoveries of such men as Young, Davy and Faraday. Rumford's remaining years were devoted to scientific pursuits.

It was in the course of his duties in Bavaria that Rumford made the discovery which has secured him a permanent niche in the edifice of modern physics. He was boring cannon in the military workshops when he became very much impressed with the amazing quantity of heat liberated by the grinding of the boring-tool against the gun. The grinding instrument was operated by horse-power, and Rumford seemed able to develop any quantity of heat by this method. His most astounding demonstration was to boil water with the heat of friction. About the portion of the cannon where the boring was being done, he built a tight box, which he filled with water. In two hours and thirty minutes, to the astonishment of the multitude, the water boiled.

In a paper read before the Royal Society in 1798, Rumford opposed the current idea that these large quantities of heat had been produced by the escape of caloric. He boldly returned to the earlier theory of Boyle, Newton and Bacon that heat is a mode of motion. The igneous fluid called caloric had indeed received a severe blow. Like the mud turtle with its head cut off, the caloric theory was dead but it did not know it. Rumford in a letter to a friend said, "I am persuaded that I shall live a sufficiently long time to have the satisfaction of seeing caloric interred with phlogiston in the same tomb."

Davy now came forward with a demonstration still more convincing. On a day when the temperature was below freezing, he rubbed together two pieces of ice at 29 degrees Fahrenheit and obtained water at 35 degrees Fahrenheit. Although it did not seem possible that the heat for the melting could come from the surrounding air, to satisfy the skeptics Davy repeated the experiment in a vacuum. The result was the same. It was absurd to assume that the heat, or caloric, had come from the ice itself. The only thing supplied in the process had been motion, and this in some way had been converted into heat.

Conclusive as these experiments were, the caloric theory survived in some quarters for half a century. Old ideas die hard.

Just a word about Davy, before we proceed further. Both a physicist and a chemist, he was one of the most brilliant and popular of the leaders in the new school of scientific discovery. When a young man of twenty-three, his fame as the discoverer of the anesthetic properties of laughing-gas, or nitrous oxide, brought him the appointment as professor of chemistry in the newly established Royal Institution. Two years later, upon the resignation of Thomas Young, he became Director of the Institution. There, during a period of nearly thirty years, Davy made many notable discoveries, particularly the isolation of a half-dozen new elements by means of the electric current. He produced the first arc-light in history and invented the miner's safety-lamp. More important than all else, he trained Michael Faraday, the man who has probably added more to the sum total of scientific knowledge than any other researcher.

THE KINETIC THEORY OF HEAT

The experimental basis now existed for the development of an intelligible theory of heat. Not only had Rumford and Davy performed their decisive experiments, but John Dalton, famous schoolmaster of Manchester, was bringing out his experimental theory of atoms. His work upon gases and their compositions soon became so convincing that few doubted his conclusion that *the elements are made up of smallest particles called atoms, and that chemical compounds are formed by the union of these atoms in simple numerical proportions*. As we now know, atoms are not the smallest particles of matter. However, it is true that an atom is the smallest part of an element that takes part in a chemical reaction. For all practical purposes, the atom is still the working unit of the chemist.

This new knowledge regarding the granular structure of matter paved the way for a kinetic theory of heat, that is, a theory built upon the idea of heat as a mode of motion. However, this theory has to do largely with what the physicist calls molecules. Therefore, we must take a look at these important units of the unseen realms.

A molecule is the next larger unit than an atom. Molecules are the building-blocks from which chemical compounds are constructed. They consist of atoms. The smallest particles into which a substance may be divided and still retain the properties of the substance are molecules. For instance, if we were to continue the physical division of a grain of sodium chloride, ordinary table salt, into constantly smaller and smaller particles, we should at length reach a point beyond which we could not go except by chemical means. In so doing we should, however, break up the molecule into its constituent elements, sodium and chlorine. The smallest droplet of water which can exist and still be water is composed of two atoms of hydrogen and one atom of oxygen. A wealth of the most reliable experimental evidence supports this view. We are as certain of atoms and molecules as we are of the clay beneath our feet.

Suppose we have a few interesting figures regarding atoms and molecules. Dr. Paul D. Foote, of the Bureau of Standards, asserts that a pound of copper contains forty-three million million million million atoms. Without going into the evidence, we may say that it is possible to determine the relative weight of an atom with far greater accuracy than a grocer weighs his merchandise. Sir Oliver Lodge places the absolute weight of the hydrogen atom at twenty-five ten-thousandths of a grain divided by the figure *one* followed by twenty-one ciphers. It would require four hundred million atoms of gold placed side by side to measure an inch, or a quintillion to weigh a gram, slightly more than a thirtieth of an ounce. Listen to Millikan as he asserts that "we can now count the exact number of molecules in any given volume or in any known weight of any homogeneous substance with even more certainty than we can count the population of a city or a state." And think of the extraordinary precision with which he places the molecular population of a cubic centimeter of air at "exactly 27.05 billions of billions." And Sir Ernest Rutherford, one of the greatest living authorities in this field, calculates from observations on the disintegrations of radioactive substances that a cubic inch of helium gas contains precisely seventy-seven billion billion atoms. Again, Dr. F. W. Aston declares that, if an ordinary electric lamp bulb were pierced with an opening such that one million molecules of air could enter per second, it would require a hundred million years to fill the bulb. Let us assume that the atmosphere, which extends outward to a distance of fifty miles or more, should suddenly be cooled to two hundred degrees below zero on the Centigrade scale. This vast envelope of gases would form a layer of liquid air over the earth's surface only thirty-five feet thick, and there would still be oceans of space left between the molecules.

Now it is the motion of molecules about which the physicist is thinking when he talks of the kinetic theory of heat. Let us see if there is any evidence for such motion.

A lump of sugar dissolves in water and slowly diffuses throughout the whole volume. Something moves in the process. If we are correct in assuming the existence of molecules, both of the sugar and of the water, is it not reasonable to believe that this mixing of the two is due to molecular movements? You who have passed required hours in a chemical laboratory know that a tiny bulb of chlorine gas will soon disseminate throughout a whole room, scenting every particle of air. Of course, this is the result of the rapidly moving particles of the chlorine. It does not take a prophet nor the son of a prophet to guess that. And these vibrating particles, we call molecules. The aroma arising in an unventilated hall crowded with human beings is impressive. Are we to believe that these odors are the result of some subtle imponderable ether, or an incense consisting of the moving molecules of human waste? A grain of musk will scent a room for years. Inconceivably small particles of the musk demonstrably move to considerable distances. The molecules in a single grain of indigo will distinctly dye a ton of water. Here the division is almost beyond comprehension, and the motion of the particles an obvious fact.

If a layer of water is poured into the bottom of a tall glass cylinder and a layer of ether poured on top, the two will mix. In time we shall find some water in every part of the ether and some ether in every part of the water. Even solids diffuse somewhat. Two pairs of metals which have been kept in contact for years will show an intermingling in the contact layers. If a thin piece of gold leaf is placed between two blocks of lead and allowed to stand for months or years, examination will show that a little of the gold has penetrated into each block of lead. Gases diffuse most readily of all. Berthollet, a famous French chemist, connected a globe of hydrogen, the lightest of all gases, with a similar globe of heavy carbon dioxide by means of a stop-cock. He placed the globe of hydrogen above that of the carbon dioxide and opened the stop-cock. In a short time, the gases had mingled perfectly. The heavy carbon dioxide had made its way up and the light hydrogen had moved down. Evidently, the smallest particles of these gases, called molecules, were in motion. Any two gases will mix in the same way. However, where two gases are separated by a porous partition, experiment shows that the light gas diffuses more rapidly. For instance, hydrogen, which is only a sixteenth as heavy as oxygen, will pass through the pores of the partition four times as rapidly as the latter. This, of course, shows that the molecules of a light gas move with greater velocities.

The Brownian Movement affords one of the best illustrations of molecular motion. In 1827, an English botanist observed with the microscope that very small particles suspended in water were in a state of constant movement. This motion was at first attributed to currents in the water or to vibration. Careful experiments proved this supposition to be wrong. It occurs, not only in water, but in all liquids, and the smaller the particles the more noticeable the movement. And it never ceases. Liquid shut up in quartz crystals for thousands of years has been found to exhibit the Brownian Movement. Indeed, this looks like perpetual motion, but it is so only in the sense that the ceaseless evolution of heat and light by the stars is perpetual motion.

The Brownian Movement has been very carefully observed under all sorts of conditions, and Einstein has worked out the theory of it. Let us picture each small particle of the suspended substance as being perpetually bombarded on all sides by molecules of the liquid. If the particle is large, these impacts have no effect. Again, if the impacts were equal on all sides of the particle, they would neutralize one another. However, the molecules in a liquid are moving hit-and-miss with varying velocities in all directions. These impacts are irregular. It may happen that for an appreciable instant the majority of them are on one side, producing motion. A moment later, the direction has changed. Forever colliding, rebounding, jostling in a mad phantasmagoric dance of perpetual motion, these molecules produce the Brownian Movement. Taking into account the viscosity, or consistency, of the liquid and the dimensions of the particles, Einstein has shown that the experimental results coincide beautifully with the calculated movements of the molecules. Thus, the speed of their motion increases with the temperature in precisely the way that the kinetic theory predicts. Under the microscope, the energy of the motion also agrees with theory.

A beautiful example of this motion is to be found in a colloidal solution of gold, viewed with the ultramicroscope, an instrument which makes visible particles approaching molecular dimensions. Such a solution, of which we have many illustrations, lies midway between a true solution, such as ordinary salt in water, and a suspension, such as fine clay in water. In this particular case, the particles of gold stand forth like stars in the mellow haze of the Milky Way. Buffeted about by some unseen agency, these structureless disks of light dance to and fro in zigzag paths with a very rapid motion. Even colloidal gold dissolved in glass is seen to participate in this motion.

A wealth of experimental evidence of various kinds supports the view that the ultimate physical units of matter of every description—whether gaseous, liquid or solid—are in a state of constant vibration. This is the kinetic theory of matter. Just as a speeding rifle bullet, too, possesses energy, so do these vibrating molecules. At the temperature of melting ice, it is estimated that an oxygen molecule moves with a velocity of about fourteen hundred feet per second, and a molecule of hydrogen four times as fast. At normal temperature and pressure, it is calculated that about five thousand million collisions occur per second in air. It is this energy which translates itself into gas pressures and into the physical fact of heat. Thus, the earlier view of Boyle and Newton has found substantiation.

FACT AND THEORY

Did you ever beat or rub your hands together to get them warm? Then you were speeding up the molecules and increasing their energy content. In some way this more rapid motion of these physical midgets manifests itself in the physiological sense of heat. True, they are always moving, but, unless they keep a certain pace, we are not comfortable. Complaints against the landlord for not supplying the proper degree of good cheer in the shape of heat is all a matter of the molecules. On the other hand, too rapid motion produces even greater discomfort. A burn from live steam simply steps on the molecular accelerator, thereby instantaneously exciting these swarms of infinitesimally small units into a turmoil of agitation which manifests itself in a keen sense of pain. The blazing sun of a midsummer's day heats the blood, opens the pores, stimulates the activity of the sweat glands and creates a feeling of sluggishness—all because the molecules have been spurred to an unwonted gait. The rather narrow limits of temperature within which life is possible hinge entirely upon a proper regulation of the natural speed ordinances of particles so small that if those in the tiniest drop of water were enlarged to the size of average grains of sand, they would build a roadway from New York to San Francisco one-half mile wide and one foot deep. Thus we see that the issues of life and the multitudinous forms of human activity, for weal or woe, are in the last analysis simple matters of molecular motion.

A blacksmith may beat upon his anvil so vigorously as to speed the molecules to an unbearable degree of heat. Helmholtz tells of a factory room kept warm by the friction of two iron disks turned by an engine run on waste steam. Every one has enjoyed the delightfully refreshing experience of an alcohol rub. The alcohol evaporates, which simply means that the molecules push themselves farther and farther apart, thereby absorbing molecular energy from your body and producing the sensation of cold. By blowing a stream of air through a little ether in a metal cup, evaporation may be made to proceed so rapidly as to bring a layer of frost on the outside of the cup. You have sometimes held your hand in the rapidly expanding air escaping from the valve of an automobile tire, and at the same time you have felt the cooling effect. The molecules in spreading to a larger volume absorb energy in the form of heat, taking it from your hand and thus slowing down the motion of its own molecules. One who sits in damp clothes becomes chilled, because evaporation decreases the individual's molecular energy content. Hot potions induce perspiration and often break up a cold, because they start the molecules to moving more merrily. If you wish more heat in your apartment, the proper order to send down to the janitor is "Please speed up the molecules."

Now, if the expansion of a gas produces cold (a very unscientific expression), the opposite process should bring heat. In the old days, when we were accustomed to inflate bicycle or automobile tires with hand pumps, we often noticed that the barrel of the pump grew hot. Possibly, we attributed this to the friction of the piston on its walls. However, it was due much more to the compression of the gas. Its molecules were crowded more closely together and therefore the quantity of kinetic energy increased. Incidentally, the air pressure increased too. There were more impacts of molecules per second upon each square inch of the inside surface of the tire.

Both of the above effects—cooling with expansion and heating with compression—are beautifully illustrated in the liquefaction of a gas as carried out in a modern refrigerating plant. In the ammonia process, for instance, a motor-driven compressor drives the ammonia gas into a metal coil, thereby crowding the molecules together and generating heat. To carry away the heat, the coil is sprayed with cold water, which simply means that the motion of the molecules is checked. Therefore, the distances to which they rebound as a result of collisions are lessened, and the cohesive force between them becomes great enough to tame their mad dance sufficiently to form a quiescent liquid. However, through a check valve the imprisoned molecules are allowed to escape pell-mell into a set of expansion coils connected with an exhaust pump. The heat liberated in the compression is now absorbed, producing a high degree of cold, which may be used for any sort of refrigerating purpose. "Dry ice," produced in a similar way from the liquefaction and solidification of carbon dioxide, yields upon evaporation a temperature of 114 degrees below zero on the Fahrenheit scale. Liquid air gives a temperature of nearly 200 degrees below zero Centigrade. These entire phenomena of the liquefaction of gases with its attendant refrigeration result from the scientific control of molecular motion.

The liquefaction of gases forms an interesting chapter in the story of heat and molecular energy. About 1816, Faraday accidentally discovered how to liquefy chlorine by heating in a bent glass tube, closed at both ends, the solid compound of water and this gaseous element. Never before had it been suspected that it might be possible to make the physical state of a gas assume the liquid form. But this interesting discovery aroused the scientific curiosity of Faraday and his master, Sir Humphry Davy. Soon after, they began to experiment with other gases, and in the course of a few years had succeeded in liquefying all but six of those then known. These they designated as "permanent gases," for despite the utmost of cold and pressure that they could develop, each stubbornly persisted in remaining in the gaseous state. They did not know what their successors learned, that there is for each gas a certain definite low temperature, termed the "critical temperature," which must be reached before a gas will liquefy, no matter how great the pressure brought to bear upon it may be. Armed with this knowledge and equipped with better means for obtaining low temperatures, all the gases have since been liquefied. Toward the close of the century, Sir James Dewar, working in the same laboratory in which Davy and Faraday had carried out the initial researches in this field, succeeded in liquefying the most refractory of the gases, and since the rare gases of the atmosphere have been made to undergo the same process. Dewar, too, devised the standard container for keeping liquid gases, an invention identical in principle with the modern thermos bottle.

As we have seen, liquefaction of gases affords the key to present processes of commercial refrigeration. Liquid air, too, produced in prodigious quantities, is the source of industrial oxygen and of nitrogen, so important in the electric-lamp industry and for the fixation of atmospheric nitrogen. This latter industry is of strategic importance both in peace and war. The rare gases of the atmosphere are also obtained from this source—helium, whose very name is sufficient, argon, used as the inert gas in many lamp bulbs, and neon, the gas employed so widely in electric signs and which is also a key element in the success of television. For the two remaining rare gases, krypton and xenon, there are as yet no uses.

When one end of a rod of metal is placed in a bed of live coals, gradually the other end becomes hot too. In accordance with the kinetic theory, it is now easy to see that this transference of heat is due to the communication of molecular motion from the hot end of the rod to the cold. The impacts of the accelerated molecules against their more sluggish neighbors speed up the latter, and so the heat contagion spreads. We call this conduction, one of the three fundamental ways of transferring heat. Metals are good conductors, liquids poor and gases poorest. Furs are warm, because of the air spaces in them. A cave hollowed out of a snow bank is not a bad place in which to sleep. The pores filled with air between the particles of snow insulate the molecular energy of your body and conserve your bodily heat. The best heat insulator is nothing at all. Therefore, from the space between the double walls of a thermos bottle, we pump the air.

We have seen that the eighteenth-century philosophers attributed the expansion of a metal with rise of temperature to the absorption of caloric. We now understand that this physical effect is the result of increased molecular energy. The molecules need a larger degree of freedom for their movements and push one another farther apart.

How hot can it get and how cold can it get? To the former of these questions we have no answer. There is no theoretical limit to the speeds which molecules may attain. The surface temperature of the sun is estimated at about six thousand degrees Centigrade. In the interior, it reaches many millions of degrees. In the depths of interstellar space, the temperature may reach rock bottom, or Absolute Zero, an expression which calls for explanation.

It is easy to see that, if the motions of the molecules should cease, there would be no energy of heat. We should have reached perfect cold, or Absolute Zero. But does this molecular motion ever cease? To Lord Kelvin we are indebted for much of the experimental work in this field. He and others have shown that the volume of gas at 0 degrees Centigrade expands 1/273 for each degree through which it is heated or contracts the same fractional part for each degree that it is cooled. Evidently, if we could continue the cooling to 273 degrees below zero, it might seem that the gas would be annihilated. However, before this low temperature is reached all gases become liquids, and this rate of contraction ceases to prevail. Yet, it is also true that for each degree a gas is cooled below 0 degrees Centigrade its pressure decreases by 1/273. That is, the motion of its molecules has been slowed down by this fractional amount. Presumably, if we could continue this cooling to 273 degrees below zero, the motion would cease entirely. In fact, there is no reason for thinking otherwise. That temperature is called Absolute Zero. It is the polar star of low temperature researches, and in the liquefaction of helium we have come within 0.9 of a degree of reaching it. At this temperature, all gases and liquids would become solids, and doubtless substances would take on peculiar and unwonted properties.

Before leaving this consideration of the nature of heat, three important discoveries must be mentioned. So far, we have concerned ourselves only with the source of heat. However, even in the latter years of the eighteenth century and the first half of the nineteenth, it was found that radiant heat, the form of energy which emanates from a hot body and passes through a vacuum as readily as through the air, possesses properties which seem to establish its kinship with light. Sir William Herschel (1738-1822), great British astronomer and discoverer of Uranus, found that the spectrum gives heat as well as light. However, these heat effects occurred most abundantly in the invisible portion of the spectrum, just preceding the red. Herschel placed a very sensitive thermometer in this spectral region, called the infra-red, and found that for some distance it indicated not only a temperature higher than that of the room but also higher than the temperature of the visible spectrum red. Furthermore, he showed that this invisible radiation can be reflected and refracted just as visible light is.

Then, in 1837, James David Forbes, a Scottish physicist, succeeded in polarizing radiant heat as well as refracting it. About the same time, too, Macedonio Melloni, an Italian physicist, demonstrated a complete parallelism between heat rays and light rays. He proved that the term *color* can be applied to heat radiation as well as to light, it being simply a matter of wave length. The only difference is that the eye is unable to perceive the color of heat.

In another chapter additional light will be thrown upon this subject of heat and its nature. We already see that it has been lifted from the delightful regions of unfounded speculation to the realm of scientific certainties. One of the most reluctant of the imponderables to surrender its throne, caloric no longer has any standing in court. The ether, the last of the hierarchy, may, too, be compelled to follow in its turn. Its prestige is being badly shaken.

PUTTING THE MOLECULES TO WORK

We have already intimated that heat is a form of energy. Indeed, the investigation of heat and its ability to do work were largely instrumental in the establishment of the nineteenth-century concept of energy, one of the distinct contributions of that period to the science of physics. Until about the middle of the century, the idea of energy as distinct from force was not clear. For some time, however, *vis viva,* or living force, the ability to do work which a body acquires by reason of its velocity, had come to be recognized. Gradually, this peculiar kind of force came to be called energy, and the meaning of the term was extended to include molecular motion. Although associated with matter, energy was looked upon as something decidedly more immaterial. The fact, too, that radiant energy in the form of waves is able to traverse the interstellar spaces, where there is no matter, tended to assign to it a nature even less material than that of the ancient imponderables. When it was recognized that this molecular motion called heat was identical with the fictitious caloric, the latter received its death blow, and the larger concept of energy assumed the leading rôle in the drama of physical phenomena.

The distinguishing characteristic of energy is its ability to do work. That heat possesses this quality, the industrial revolution created by Watts' invention of the steam-engine left no doubt. Even earlier, heat was known to be a large factor in the destructiveness of gunpowder. Gradually, the idea became orthodox that the energy of vibrating molecules is a chief source of power. Forthwith, in even larger measure than before, these willing servants were harnessed to do the world's work.

Still, scientists were by no means out of the woods on this matter of energy and work. No working agreement, so to speak, had been established between the two. No definite relationship between the expenditure of a given amount of energy and the production of a corresponding amount of work had been discovered. No law of the Conservation of Energy was known. Indeed, until well past the first quarter of the nineteenth century it was the universal belief that force, or energy, could be annihilated. Everywhere energy disappeared—seemed to be dissipated. Perpetual motion was a will-o'-the-wisp, sought after as the Philosopher's Stone had been in the preceding centuries. Loose ideas regarding the possibility of creating energy prevailed. There seemed to be nothing illogical about this belief. Although energy appeared to be lost, it might with equal propriety be created. Such notions were at the bottom of the mad orgy of perpetual-motion schemes which ran riot a century ago.

However, the will to believe in perpetual motion or something better was not the exclusive property of the simple-minded folks of the early nineteenth century. In a Brooklyn courtroom not so many years ago, a venerable-looking old gentleman was tried and convicted on the charge of obtaining money under the false pretense of being able to manufacture gasoline from Long Island moss. Another of the recent tribe of get-rich-quick gentry extracted thousands of dollars from thrifty, hard-headed New Englanders in exchange for stock in a process for extracting gold from sea water. Probably as unique an example of the childlike simplicity with which belief in the possibility of creating energy is accepted by some occurred in connection with liquid air about a generation ago. One man who actually did produce liquid air in quantity asserted, and his assertion was received by many in good faith, that from the energy in one gallon of his liquid product he could manufacture ten more. He had devised an engine which he ran on the expanding gases from liquid air, and this ran the compressor which liquefied the air. To many, his claim seemed plausible enough, for he needed no fire to vaporize his liquid. The heat of the surrounding atmosphere did that. Of course, this man fooled no one but the public. Had his extravagant statements been true, he would have had perpetual motion itself beaten ten times. The surprising thing about it all is that people now living were gullible enough to believe such tales.

Although the repeated failures of perpetual-motion projects did not much discourage further attempts, they did set many to thinking about the relation of a given quantity of energy to the amount of work it would do. Heresy though it might be to think it, some there were who became convinced that energy is not annihilated in mechanical changes. They believed that energy apparently lost is converted into heat, for it had been observed on innumerable occasions that whenever mechanical energy disappears, heat is always produced.

The first man to attack this problem in a scientific way was a brilliant Frenchman, named Sadi Carnot. As early as 1824, he had provided the basis for the modern science of thermodynamics. Although hampered by a belief in the hypothetical caloric, he established the theory of the steam-engine, and of all heat engines for that matter. Furthermore, emerging from his investigations came two laws, fundamental to an understanding of the relationship of energy and work. For the first time, he clearly recognized that not only can mechanical energy be converted into heat but that the reverse is also possible, and that the transformations are quantitative. Taking a hydraulic power plant as an analogy, Carnot argued that, just as there must be a fall of water to produce mechanical energy, so must there be a corresponding fall of temperature to cause a steam-engine to do work. Without this fall of temperature, no heat is converted into work. In every instance, the heat involved is the measure of the energy transformed. This in substance is the First Law of Thermodynamics. It is really a special case of the fundamental law of the Conservation of Energy, regarded as the most remarkable generalization of physics in the nineteenth century. Carnot did not prove experimentally his principle, now known as the mechanical equivalent of heat. However, another soon did, and several at about the same time arrived at this larger concept of the Conservation of Energy. To their investigations, I now invite your attention.

In 1837, Karl Friedrich Mohr, a German, had grasped the main truth of the new principle. He published an article setting it forth, but it attracted no attention, not even from his own countrymen. In fact, it may be said that all of these pioneers received a cold reception. Possibly the fact that this law in its full significance vetoed the theoretical and practical possibility of perpetual-motion schemes had something to do with the attitude of contemporary theorists. But be that as it may, the scientific world was reluctant to accept the new point of view. Ludwig August Colding, of Copenhagen, also arrived at a similar conclusion regarding energy and work, but to Robert Mayer, a German physician, must be given credit for the first actual calculation of the value of the mechanical equivalent of heat as a general principle.

Mayer, a native of Heilbronn and an indifferent student, attended the gymnasium and the theological school and afterward studied medicine at Tübingen. He displayed no great aptitude for his profession, but in 1840 he made a trip to Java as surgeon on a Dutch vessel. There in the tropics Mayer made the important observation that blood drawn from the vein of a patient almost without exception possessed a bright red color. I say "important," and yet this circumstance may be so described only because it happened to come under the notice of a man who had the ability to think and to draw conclusions of a scientific nature from what he saw. Strange, that this chance discovery should have marked the real beginning of the establishment of the most important generalization in nineteenth-century physics, but such it did.

In those days, bleeding patients, even for the slightest disorder, was the common practise. At home, Mayer had been accustomed to seeing blood of a bluish tinge come from the veins of Europeans. The fact that in the tropics venous blood under the same circumstances should be red arrested his attention. He says: "This phenomenon riveted my earliest attention. Starting from Lavoisier's theory according to which animal heat is the result of a process of combustion, I regarded the two-fold change of color which the blood undergoes in the capillaries as a sensible sign or visible indication of an oxidation going on in the blood. In order that the human body may be kept at a uniform temperature the development of heat within it must bear a quantitative relation to the heat which it loses, a relation that is determined by the temperature of the surrounding medium; and henceforth the production of heat and the process of oxidation as well as the difference in the color of the two kinds of blood must be on the whole less in the torrid zones than in the colder regions. Hence it follows that a general balance must be struck in the organism between the receipt and expenditure or between the work done and the wear and tear. . . . Wear and tear consists in the amount of matter consumed. The work done is the evolution of heat.''

Here was a man with the insight of genius likening the human mechanism to a machine illustrating the quantitative relationship between heat and work. To him, the red blood issuing from the veins of patients in the tropics simply meant that less oxidation was taking place in the organism. The higher temperatures prevailing in those parts checked the radiation of heat from the body and necessitated the burning of less bodily fuel. He perceived that between the ''wear and tear,'' as he put it, and the heat evolved must be an undeviating relationship of a quantitative nature.

Probably Mayer displayed even greater genius in the clear insight with which he saw the bearing of this conception on the whole problem of energy. He says, ''This is a question that touches the very foundations of science, and unless it receives a trustworthy answer the healthy development of the doctrine concerned is not possible.''

But this German physician did not stop there. Using tables of the specific heats of gases prepared by Regnault, he actually calculated the amount of mechanical work done by an expanding gas during the absorption of a certain amount of heat. Taking into account the fact that Regnault's tables were not entirely accurate, his result was almost precisely the same as that later determined by Joule.

Two years after his observations in Java, Mayer published a paper entitled ''On the Forces of Inorganic Nature,'' giving the results of his reasoning and work. Although this has come to be recognized as one of the most important contributions in the whole history of science, the paper was rejected by one of the leading scientific publications in Germany. Finally, Liebig accepted it for the May, 1842, issue of his *Annalen*. A second paper in 1845, elaborating his ideas, could be published only at private expense.

The following story is told by Mach, a writer in the *Monist* of 1896: "During a hurried meeting with Mayer in Heidelberg once, Jolly remarked, with a rather dubious implication, that if Mayer's theory were correct, water could be warmed by shaking. Mayer went away without a word of reply. Several weeks later . . . he rushed into the latter's presence exclaiming: '*Es ischt so!*' (It is so, it is so!) It was only after considerable explanation that Jolly found out what Mayer wanted to say."

Mayer's later life was particularly unfortunate. Depressed by the vigorous controversy aroused over his rights of priority of discovery and also by the deaths of two of his children, his mind became affected. In 1849, he unsuccessfully attempted suicide, and later was placed in an insane asylum, where he was inhumanly treated. John Tyndall translated a number of his papers and in a series of lectures before the Royal Institution in 1862 attempted to do justice to his memory. However, Tyndall was accused of belittling the work of his own countryman, Joule.

Now we must give attention to James Prescott Joule, a Manchester brewer whose name will forever be identified with the first experimental demonstration of the mechanical equivalent of heat and its accurate determination. Refused appointment as professor of natural philosophy at St. Andrews, Scotland, because of a slight physical deformity, he remained a brewer to the end of his days, but for more than forty years he carried on work as a scientific investigator. Let us observe, too, that Joule's work, as well as that of his contemporaries in this field, was done without knowledge of any other similar researches.

Joule began his experiments in 1840. He contrived an apparatus for making a number of brass paddles revolve in a closed cylinder of water by means of a falling weight. The water in the cylinder was carefully weighed in advance and a delicate thermometer was inserted to measure the increase in temperature. The weight, of known mass, was allowed to fall through a measured distance, thereby making it possible to determine the amount of work done upon the water by taking the product of these two factors. Joule's theory was that the friction of the paddles would heat the water and, if his cylinder were properly insulated to prevent loss of heat by conduction and radiation, the thermometer would record a rise in temperature.

The experiment worked precisely as Joule had predicted. Fact and theory corresponded beautifully. Over and over, he made the determination, and always with practically the same results. Thinking that the materials of his apparatus might have something to do with the amount of heat developed, Joule made three types of experiments. In the first, he used water in a brass vessel fitted with brass paddles; in the second, he substituted mercury in an iron vessel and employed an iron paddle; while in the third, he caused two iron rings to rub against each other in mercury. With all three, the results were fairly close together. Always, practically the same amount of work was required to heat a given quantity of water through the same temperature. Here was the mechanical equivalent of heat put into concrete terms. It was no longer a mere matter of theoretical speculation, for Joule found that 772 (later 778) foot pounds of work were needed to raise one pound of water through one degree Fahrenheit. This latter quantity is known as the British Thermal Unit, and thenceforth its value in terms of mechanical energy became 778 foot pounds. And we remember that a foot pound is the amount of work done by a force of one pound acting through a distance of one foot. For instance, in Joule's experiment a ten-pound weight would need to fall through 77.8 feet in order to produce a unit of heat.

Again, just as in the case of Mayer, Joule's efforts to get his discovery before the public met with a degree of opposition comprehensible only in the light of the frequent obtuseness of "great" leaders to the reception of new ideas. In 1843, he read his first paper on the subject before the British Association for the Advancement of Science, but it received no serious attention. In April, 1847, he gave a popular lecture in his home city of Manchester in which, it is stated, he presented "the first full and clear exposition of the universal conservation of that principle now called energy." The local press received the announcement with indifference. Only one paper, the *Manchester Courier*, condescended to publish the address, and that not until after it had been the subject of long debate. When in June of this latter year Joule presented the subject before the Oxford meeting of the British Association, the chairman requested the speaker to be brief, and following invited no discussion. Had not a young man named William Thomson, later to become Lord Kelvin, risen to his feet and "by his intelligent observations created a lively interest in the new theory," an epoch-making paper would have passed into temporary eclipse. As it was, Joule's discoveries created a sensation, and he came prominently to the attention of scientific men. So slowly did scientific ideas travel in those days that it was not until Joule talked with Thomson after this meeting that he learned of Carnot's theory regarding the steam-engine.

In the year which saw Joule's formulation of the principle of the Conservation of Energy, Hermann von Helmholtz, one of the most distinguished physicists of the last century, read a paper on the same subject before the Physical Society in Berlin. Helmholtz began his career as a physician and surgeon, later becoming a teacher of anatomy at Berlin and afterward professor of physiology successively at Königsberg, Bonn and Heidelberg. In 1871, he became professor of physics at the University of Berlin. Seldom does one become a master in so many fields, for Helmholtz took first rank as a physiologist, a mathematician and a physicist. W. K. Clifford once said of him: "In the first place he began by studying physiology, dissecting the eye and the ear, and finding how they acted, and what was their precise constitution; but he found that it was impossible to study the proper action of the eye and ear without studying also the nature of light and sound, which led him to the study of physics. He had already become one of the most accomplished physiologists of this century when he commenced the study of physics, and he is now one of the greatest physicists of this century. He then found it impossible to study physics without knowing mathematics; and accordingly he took to studying mathematics, and he is now one of the most accomplished mathematicians of this century.'' (Written in the last century.)

When only twenty-six, Helmholtz read his famous paper in Berlin. However, just as in the case of Mayer, scientific journals refused it publication. Influential friends supported his view, and the paper was published in pamphlet form in 1847. Although he had had no knowledge of other work in this field, Helmholtz was charged with having purloined his ideas from the investigations of contemporaries.

This law of the Conservation of Energy may be stated as follows: *''Energy can neither be created nor destroyed, but it may be changed from one form to another.''* It was implicit in Newton's Laws of Motion, and Dr. Arthur Haas, professor of physics at the University of Leipzig, says, ''The law of the conservation of mechanical energy is to be found in precise form in the works of Lagrange even in the eighteenth century. Helmholtz was the first to show in an exact manner (in 1847) how the law can be applied also outside the realm of mechanics (in the narrower sense of the word).''

Max Planck, author of the famous quantum theory of energy, makes the following illuminating comment, ''There are only two kinds of energy in Nature, kinetic and potential, and when considering any particular form of energy, e. g., heat, electricity, magnetism, it has simply to be decided whether it is kinetic or potential. This is the attitude adopted by Helmholtz in his first epoch-making paper on the conservation of momentum. A certain time elapsed before it was realized that nothing regarding the nature of energy follows from the law of conservation of energy. This was advocated from the beginning by Julius Robert Mayer, the discoverer of the mechanical equivalent of heat.'' Although scientists had identified energy as a quantity distinct from force, its real nature was and is as much in the dark as ever.

To William John M. Rankine, professor of engineering and mechanics at Glasgow during the middle of the last century, we are indebted for the expression ''conservation of energy.''

With the establishing of this law, the molecules were sitting on the throne of majesty. Steam had come to be the motive power of material civilization, and in steam molecular motion rules supreme. No one longer doubted that heat is a mode of motion, due to the ceaseless vibrations of these physical units. And the highway between heat and mechanical work had been cleared for all time. When one discussed such phenomena, he now talked in terms of an intelligible science. The conception of molecules and their behavior had provided the key.

THE SECOND LAW OF THERMODYNAMICS

No other principle of physics has received more consideration in the last half-century than the Second Law of Thermodynamics. When you discover that upon the truth or falsity of the manifest implications of this law may depend the future existence of this world and your own personal welfare in a subsequent incarnation some billions of years hence, you, too, may sit up and take notice.

First, let us state the law as it was formulated by its two chief expounders, Clausius and Lord Kelvin. Clausius' version runs as follows, ''It is impossible for a self-acting machine, unaided by any external agency, to convey heat from one body to another at a higher temperature, or heat can not of itself (that is, without compensation) pass from a colder to a warmer body.''

Kelvin put it thus, "It is impossible by means of inanimate material agency to derive mechanical effect from any portion of matter by cooling it below the temperature of the coldest of surrounding objects." Kelvin, too, closely associated this law with his doctrine of the dissipation of energy.

Nothing in all this sounds very profound. We are not in the habit of heating our houses with cakes of ice or deriving good cheer from dyspeptic pedlers of pessimism. We do not try to make water run up-hill, nor practise walking on our heads, because it is so much easier in each case to do the opposite. We should not expect unburned coal in the fire-box of a locomotive to produce steam, if the water and coal were at the same temperature. Unless the molecules in one body are scurrying about at a more rapid rate than they are in another, no one believes that any increased molecular motion can be conveyed from one to the other. No more than water, will energy flow from a lower to a higher level. The salvation of the world, and of the universe for that matter, depends upon the continued maintenance of a difference in energy levels. When the continents have been leveled and all the water has flowed into the sea, water-power will be gone. Likewise, when the coal and petroleum are gone and the sun has dissipated its energy, there will be no possibility of doing any more work upon this planet. And that is the sad feature of this Second Law of Thermodynamics.

Let us take other illustrations. The earth and the oceans contain vast quantities of heat energy. If in some way we could tap these reservoirs, we should have available great sources of power. Sometimes this can be done. In California and in Italy, live steam issuing from the earth is used to run turbines and dynamos. It has been seriously proposed that engineers sink shafts to depths of several miles in the earth, through which to let down water to be converted into steam for power purposes. That is, a present difference in energy levels exists between the surface of the earth and its interior. If practicable ways can be devised for allowing this pent-up molecular energy to flow to the surface, it can be utilized to do the world's work. However, the time will come when this difference in energy levels no longer exists, for the earth is cooling off, which simply means that the rate of vibration of its molecules is slowing down. Eventually, they will all, in every portion of the earth, strike the same gait. Then, while there will be vast reservoirs of latent heat, there will be no available heat. That is what is meant by the dissipation of energy.

A ship at sea without fuel is surrounded by vast quantities of heat in the molecular energy of the water, but this heat is unavailable. To take heat from the water, we should have to cool the water below its surroundings. In other words, we should have to do the same thing as make water run up-hill. This ship is smothered with supplies of energy, but there is no difference of energy levels. When differences of energy levels everywhere disappear, motion and life will come to a standstill.

However, a coal mine, an oil-well or a waterfall constitutes in each case a difference in energy levels. As long as these exist, we are all right. Unfortunately, they are disappearing, and in every energy transaction there is irretrievable waste. Only a small part of the transformed energy is expended in useful work. The larger portion escapes as heat in accordance with Joule's mechanical equivalent. It is just the same as though we had a number of bodies, all at different temperatures, shut up in a room. Immediately, the warmer bodies will begin to give up their molecular energy to the colder bodies. In time, all of them will come to the same temperature. Heat transfers will cease. Energy accounts will be balanced. They will all come to a dead level, and there will be no way to create another differential.

Again, we may think of a clock which is wound up. As the weights descend, the wheels turn. But at length the weights reach the end of their journey, and, if there is no one to wind the clock up again, its action has ceased forever. It can not wind itself. The action is not automatically reversible. Likewise, in the dissipation of energy, most processes are not reversible. While the various forms of energy are convertible into one another, these conversions do not work equally well both ways. For instance, although mechanical work can be readily and completely converted into heat, the reverse transformation of heat into other forms of energy can be only partly carried out. Let energy once get into the form of heat and it is impossible to get it all out again. In most energy transformations heat is a product, and much of it becomes immediately unavailable for further use. Therefore, the proportion of unavailable heat energy in the universe is constantly increasing, and the time will come when no further energy transformations are possible.

That is the essence of the Second Law of Thermodynamics. It is often called the degradation of energy. Clausius coined the word *entropy* to express this state of affairs, and put the principle this way, "The entropy of the universe tends to a maximum, and its available energy to a minimum."

If we consider the sun, the primal source of all our earthly energy, we find that its vast supply is constantly being radiated into space at a prodigious rate. What becomes of it? A small part chances to do a little work upon the members of the solar group, but the bulk of it passes on. Our earth intercepts but one two-billionth of the sun's radiation. Does the vast remainder become merged in a cosmic reservoir of latent but unavailable energy? Are we, as Professor Jeans pictures us, like polar bears adrift upon an iceberg floating toward equatorial waters, soon to be swallowed up in the abyss about us? Is there no reverse process discoverable? Will the clock never be wound up again? Are we drifting helplessly, irresistibly, toward a cosmic night, possibly an everlasting sleep, the "twilight of the gods"?

Inexorable and inevitable as the working of this law may appear to be, there are those who think they see the silver lining behind the cloud of gloom. Possibly, it is only a local law for our particular ''neck of the woods,'' and not a general statute for the whole cosmos of time and space. That there is tangible evidence for some sort of a rewinding of our universe, we shall see in another place.

MATTER AND ENERGY

In passing, let us note a point which will be discussed more fully in another chapter. Matter and energy are no longer regarded as distinct and independent entities. Energy has become the overshadowing concept. Matter is now regarded as electrical in nature and convertible into energy. Indeed, Einstein has worked out the precise mathematical equation governing the transformation. It is this dissipation of mass to produce energy that is responsible for the celestial fires. The Law of the Conservation of Matter has been swallowed up in the larger concept of the Conservation of Energy. Energy, too, possesses inertia, and matter is simply the inertial aspect of energy.

It follows from the foregoing that a terrestrial body which loses energy in the form of light and heat must also lose inertia. In other words, it loses some of its mass, and therefore should weigh less. Although this loss is far beyond the limits of practical measurement, it can in any given case be theoretically calculated. For this reason, we say that, while the Law of the Conservation of Matter still holds for all practical purposes, its earlier prestige has gone. Matter is not indestructible as such. Regarded as an aspect of energy, however, it is.

If we were to pass an electric current through water, thereby separating the latter into its constituent elements, hydrogen and oxygen, we should be giving to it potential energy. Therefore, the energy content of the gases being greater, their weight should be slightly in excess of the weight of the water before the electrolytic action took place, for energy is equivalent to mass. Conversely, if these gases are now exploded, energy in the forms of light and heat will be given off, and the resulting mass will be slightly less than before the explosion occurred. In fact, it will be identical with that of the original water.

We have now traced the evolution of the concept of heat in the light of yesterday and to-day. Still, we are not permitted to write finis across the chapter, for to-morrow may bring a yet larger view.

CHAPTER V

The Rise of Electricity

DISCOVERY—MAGNETISM—TALES OF ANTIQUITY—MARINER'S COMPASS—GILBERT, "THE FATHER OF ELECTRICITY"—HIS DISCOVERIES—EXPERIMENTS BY GUERICKE—FIRST ELECTRIC LIGHT—DISCOVERY OF CONDUCTORS—STEPHEN GRAY—KINDS OF ELECTRIFICATION—LEYDEN JAR—CONTRIBUTIONS OF FRANKLIN—LIGHTNING—VOLTAIC ELECTRICITY—GALVANNI—VOLTA INVENTS THE ELECTRIC CELL—DISCOVERIES OF DAVY—OERSTED AND ELECTROMAGNETISM—CONTRIBUTIONS OF ARAGO AND AMPÈRE—OHM'S LAW—INVENTION OF THE ELECTROMAGNET—FARADAY—DISCOVERY OF INDUCED CURRENTS—THE LAW—LINES OF FORCE—EXPERIMENTAL BASIS—FARADAY'S LATER WORK—DISCOVERY OF OTHER MAGNETIC SUBSTANCES THAN IRON—WORK OF JOSEPH HENRY—ELECTROMAGNETIC THEORY OF LIGHT—MAXWELL—ELECTROMAGNETIC WAVES—NEW CONCEPTION OF ETHER—HERTZ VERIFIES PREDICTIONS OF MAXWELL—IN THE WAKE OF MAXWELL AND HERTZ—PRESSURE OF LIGHT.

When perchance some caveman may have rubbed an ornament of amber against his furskin coat and thereby discovered a new and wondrous property, no record discloses. Certain it is, however, that in that moment the science of electricity was born. *Electron,* the Greek for amber, gave the name and is to-day retained to designate one of the two ultimate units of physical creation. The attractive influence of rubbed amber undoubtedly goes back to the very dawn of civilization. Beads of amber, found in the royal tombs of ancient Mycenæ, prove the existence of a traffic in this highly prized substance of antiquity even in prehistoric times. The Phœnicians, pushing their tiny crafts beyond the "gateway of the world," brought amber from the shores of the Baltic. Thales of Miletus, in the seventh century B. C., is the first man in the historical record to be credited with a knowledge of this mysterious influence.

Although the significance of this discovery was to lay dormant for two thousand years, out of it came one of the most prolific fields of scientific research, remarkable alike for its revelations and for its influence upon the progress of civilization. Matter and energy, in their ultimate analysis, appear to be electrical in origin. No other word in the language has become more freighted with import, theoretical and practical, than has electricity. In the last half-century of progress, the word *electrical* has come to be a name to conjure with. In the popular imagination, nothing has seemed too wonderful for belief if only this magic symbol could be offered in explanation. Such a bewildering array, too, of substantial triumphs has passed with kaleidoscopic rapidity before the public eye that electricity has often seemed to afford the long-sought key to the solution of a thousand problems.

THE PROPERTY OF MAGNETISM

Electricity and magnetism can no more be dissociated than left and right or time and space. In modern times the story of magnetism precedes that of electricity. It began with the writings of Peregrinus in the thirteenth century. The mariner's compass had preceded his investigations, the earliest references to it in the literature of western Europe dating from the latter part of the previous century. In the *Epistola* of Peregrinus we find an account of a spherical magnet which he had made, and how to locate the north and south poles, the names which he gave for the meeting-points of the magnetic meridians. He seems to have been acquainted, too, with a number of magnetic properties, later rediscovered by other workers

Many stories are told by early writers regarding this mysterious influence. We are all familiar with the tale of the shepherd Magnes who, while tending his flocks on the slopes of Mount Ida, was astonished to find his iron crook and the nails of his sandals adhering to a large black stone. In time, this stone came to be called the "Magnes Stone," or magnet, and thus the tradition has been immortalized. We now call it magnetite. Pliny tells of a wonderful vaulted roof constructed of magnetite in the temple of Arsinoe, in which an iron statue of the queen was suspended in mid-air. From this story, too, grew the legend regarding the suspension of Mohammed's coffin. The Middle Ages were rife with such fables. We read of magnetic mountains that were reputed to have pulled iron nails from ships, even at a considerable distance, drawn vessels to destruction and moved the compass needle far astray.

The iron mines of antiquity were located on the Mediterranean islands and along the coast of the Ægean Sea. Probably the name magnet originated in the fact that magnetic iron ore was found near Magnesia in Asia Minor. Knowledge of the properties of the lodestone, or "leading stone," was undoubtedly known to primitive peoples. The observation that a suspended bar of this ore will place itself along the meridian and point to the north was quite likely an ancient discovery. In all probability this preceded the art of metallurgy. Then, with the smelting of iron ore came the discovery that bits of iron rubbed against the lodestone also became magnetic. How some primitive man must have pondered in deepest wonder over this remarkable fact! So should we, had not this property been a commonplace from childhood. Miners on the island of Samothrace, where iron ore was found, exhibited the mysteries of the so-called Samothracian rings. Socrates in referring to these said, ". . . that stone not only attracts iron rings, but also imparts to them a similar power of attracting other rings; and sometimes you may see a number of pieces of iron and rings suspended from one another so as to form quite a long chain; and all of them derive their power of suspension from the original stone." That the Greeks went much beyond these simple discoveries, there is no evidence.

The adaptation of a magnetized needle in the mariner's compass may have been made by the Chinese as early as 2000 B. C. The more credible belief, however, attributes the invention of this epoch-making instrument to the seafaring peoples of northern Europe about the middle of the twelfth century. As early as 1544, George Hartmann, a German priest, gave a complete discussion of magnetic dip, the fact that a compass needle, free to move in a vertical plane, does not remain horizontal, but points downward, the angle of dip becoming greater as the compass approaches the earth's magnetic pole. The first announcement of this was made by an English compass-maker, Robert Norman, in 1576. More than a century before, in 1436, Andrea Bianco, an Italian, had published charts showing lines of magnetic variation, that is, the deviation of the needle from the true geographic north. Yet, in 1492, we find Columbus' sailors frightened because of the rediscovery of this phenomenon.

Magnetism now was to share with electricity the interest of scientific men, and two centuries later the two were linked in a relationship which was to be a guiding factor in all subsequent research in this field.

WILLIAM GILBERT, "THE FATHER OF ELECTRICITY"

William Gilbert, or Gilberd as he wrote himself, born in 1540, in Colchester, England, twenty years before the birth of Galileo, was the originator of the modern science of electricity. Being the son of a man of some prominence, he was given a good education, including, as was customary in those days, travel on the Continent, after which he became a practitioner of medicine in London with the pursuit of science as his hobby. In his chosen field of magnetism and electricity, he was as exact an experimenter as Galileo. Unmerciful was he in his chastisement of superficial retailers of unverified assertions regarding natural phenomena. Nothing passed muster with him until he had put it to the most rigid experimental tests.

Gilbert was a man of eminence in his profession, for he was elected a Fellow of the Royal College of Physicians, later becoming its president, and as is well known, he was appointed Chief Physician to the Court of Queen Elizabeth, retaining the position with James I after the death of the queen. In 1603, he died, and in 1666 all of his priceless records and instruments were lost in the Great Fire.

Up to the time of Gilbert no distinction had been made between the property exhibited by the lodestone and that of rubbed amber. For the first time, he pointed out that, while amber would attract light objects of all descriptions, a magnet would attract only iron. Strange that this circumstance had escaped all earlier observers, but so it had. Gilbert also showed that, although iron was the only substance then known capable of being magnetized, amber shares its property of attraction with many other materials. He coined the terms *electrics* and *non-electrics*, substances which, respectively, exhibit attractive properties when rubbed and those which do not. He did not discover that the latter are simply better conductors, exhibiting these same manifestations when insulated so as to prevent loss of the "virtue." In passing, let us observe that the word *electricity* to designate this whole realm of phenomena was first used by Sir Thomas Browne about a century later. Gilbert, too, invented a crude sort of electroscope, a *versorium* he called it, for detecting electric charges.

Still, Gilbert's most important service was in the field of magnetism. He demonstrated that the earth itself is a huge magnet. In no other way could he account for the behavior of the compass needle. In support of his belief, he shaped a small sphere from lodestone and explored its surface with a short magnetized needle suspended by a thread. Just as he had expected, this needle behaved exactly the same as does the compass needle with respect to the earth. On either side of the magnetic equator of his "little earth," the needle would "dip" away from the horizontal, just as the compass needle does. At the magnetic poles, it assumed a vertical position. Gilbert, too, imagined a field of force surrounding the earth, just as Faraday did more than two centuries later. Following this experimental work, it was less easy to believe that the seat of magnetic attraction lay in the stars of heaven.

Gilbert was familiar with the fact that a magnet loses its magnetization with jarring and also by heating. From this it is altogether likely that he inferred magnetism to be a property of small particles of the substance, the molecules of modern science.

In his great work, *De Magnete,* Gilbert left a record of immense historic interest. A brief passage from it will show his mode of thought:

> "The common herd of philosophers, in search of the causes of magnetic movements, called in causes remote and far away. Martinus Cortesius . . . dreamt of an attractive magnetic point beyond the heavens, acting on iron. Petrus Peregrinus holds that direction has its rise at the celestial poles. Cardan was of the opinion that the rotation of iron is caused by the star in the tail of Ursa Major. The Frenchman Bossard thinks that the magnetic needle turns to the pole of the zodiac. . . . So has ever been the wont of mankind; homely things are vile; things from abroad and things afar are dear to them and the object of longing."

Because of Gilbert's desire to make terrestrial magnetism support the Copernican doctrine, he made extravagant statements in his work, not warranted by fact or theory. For this reason his *De Magnete* fell into neglect following his death, and it was not until recent times that his great contribution came to be recognized.

THE BURGOMASTER OF MAGDEBURG

The first man to devote his spare moments to experimenting exclusively with electricity proper in distinction from magnetism was Otto von Guericke, burgomaster of

Magdeburg. Born of a prominent family, he was educated in German universities and at Leyden, later traveling in France and England. During the stormy period of the Thirty Years' War, he conducted numerous diplomatic missions and at one time became an engineer in the army of Gustavus Adolphus. As we have seen, his early scientific exploits were with the air-pump, which he invented. However, he is remembered equally well for his work in electricity, being the inventor also of the first electric machine.

This machine consisted of a ball of sulfur, mounted on an iron axis free to turn. By rotating the globe against the palm of his hand, he was able to electrify it, so that it would attract "all sorts of little fragments, like leaves of gold, silver, paper, shavings, etc." Despite more than two thousand years of familiarity with this attractive property of matter, no one before seems to have discovered the fact of electric repulsion, at least not sufficiently to have commented on it. Guericke came into possession of this bit of information by observing that a feather was first attracted by his electrified sulfur and then repelled. More important still, he announced that the electric "virtue" may be conducted along a linen thread and will become manifest at the farther end. In this, he anticipated the experiments of Stephen Gray. Here was the world's first line for the transmission of electric energy. To the astonishment of the burgomaster, he found that in a darkened room a glow of light appeared about his rotating globe, accompanied by a crackling noise, described by Guericke as the "virtue of sound." So far as we know, this is the first instance of an artificial electric light. Little did this pioneer explorer of an unknown realm realize that he might some day be termed the forerunner of a system of lighting which was to flood the world with its sunlike radiance.

As unfortunate as were Gilbert's magnetic speculations regarding the cosmos was Guericke's identification of gravitation and electric attraction. He imagined the earth to be a "vast electric machine rotated by the hand of the Almighty and excited by the friction of the solar rays." However, his will always be an honored name, for he opened wider the door to a knowledge of electric phenomena.

THE VACUUM LIGHT

In his experimenting with the air-pump, Boyle observed that electric attraction takes place through a vacuum. Later, toward the close of the seventeenth century, the accidental discovery of a phosphorescent glow in the vacuum above the mercury in a barometer tube attracted widespread attention. Jean Picard, a French priest, in carrying the apparatus from Paris to the Porte Saint Michel after nightfall, noticed that each motion of the mercury caused a glow in the Torricellian vacuum. At first the mysterious light was attributed to a hypothetical substance designated as mercurial phosphorus, so easy was it in those days to assume a special medium for the explanation of any new phenomenon.

Francis Hauksbee, curator of experiments at the Royal Society in London, determined to go to the bottom of the thing. He began a series of experiments which from the first gave astonishing results. Under the bell jar of an air-pump he placed a dish of mercury and exhausted the air. Then, through a glass tube dipping beneath the surface of the mercury, he let air rush in, producing a fountain. As he watched, Hauksbee saw the air blowing the mercury upward "with violence against the sides of the glass that held it, appearing all round as a body of fire, made up of abundance of glowing globules descending again into itself." He next mounted an exhausted globe so that it might be rotated rapidly and, holding his hand against it, produced a beautiful purple glow, so bright that it filled the room and made possible the reading of large print. Even though they did not touch it, one's fingers held near to the excited globe were said to become phosphorescent with brilliant patches of light. Marvelous happenings were these—discoveries which helped to build the growing edifice of electricity. Hauksbee concluded that both motion and a partial vacuum were necessary for the production of the light. Inasmuch as the phenomena were accompanied by attraction, he attributed them to electricity.

Hauksbee, too, made other electrical investigations. Holding an electrified glass rod near to his face, he felt the "electric breeze," accompanied by sparks and a crackling "like green leaves in the fire." He carried out experiments on attraction and repulsion and found that the electric charge is dissipated in moist air. He it was who first noted that an electric charge resides only on the surface of a body and that metals may be electrified by friction.

THE DISCOVERY OF CONDUCTORS

In the early part of the eighteenth century, at the time when Newton was at the zenith of his glory, Stephen Gray, an irascible old pensioner of the Charterhouse, was making, purely for his own amusement, experiments which not only served to immortalize his name, but which contributed one of the most important discoveries to the growing science of electricity. The materials for his simple tests were glass tubes, fishing-rods, hemp twine, pieces of brick, blocks of resin and Gray Friars lads.

Guericke's proof that the electric virtue will pass through a linen thread had long since been forgotten. With his interest deeply aroused in this new phenomenon of electricity, Gray began to ponder as to whether this effect could not be communicated to other bodies. There was only one means of knowing. He must experiment. The most available material were his fishing-rods and some glass tubing. Arranging the rods into a series eighteen feet long, to his delight he quickly discovered that an electrified glass tube placed at one end immediately manifested its influence at the other. Between a balcony and the ground, a distance of thirty-four feet, he repeated the experiment, and with the same result. Next, he suspended a hemp thread one thousand feet long by means of threads of silk placed at intervals. Over this, too, he successfully passed an electric charge. Here were excellent examples of original discovery. This man was in search of knowledge—knowledge, simple though it now seems, which the world did not then possess. However, his choice of silk was not new. Gilbert and Hauksbee had noticed that the electric attraction could be cut off by means of silk. Gray now wished to know whether other substances behaved like silk. Therefore, he suspended his hemp thread by metal wires, and found that the experiment failed. The metal apparently carried off the virtue. Thus, he arrived at the conclusion that some substances will conduct electricity and others will not, a discovery which soon received much corroboration from other workers.

Gray communicated his first discovery to the Royal Society in the following quaint language: "The Electrick Vertue of a Glass Tube may be conveyed to any other Bodies so as to give them the same Property of attracting and repelling light Bodies as the Tube does, when excited by rubbing: and that this attractive Vertue might be carried to Bodies that were many Feet distant from the Tube."

In 1729, Gray made another important electrical discovery. It was well known that a magnet will magnetize a piece of iron without actual contact. This is called magnetic induction. Gray now found that an electrified glass tube would induce a charge in a near-by object, "even a foot distant." As Hauksbee had done before him, he also observed that the charge is always on the surface of an electrified body. Most interesting of all were his experiments with Gray Friars lads. Suspending a boy by means of silk cords hanging from the ceiling, he presented an electrified rod to his feet and drew sparks from his face. Great sport that was, and the fame of Gray and his discoveries spread throughout England and even to the Continent.

It now became clear that Gilbert's non-electrics were identical with Gray's conductors, and that the so-called electrics were the non-conductors.

OTHER DISCOVERERS

At the same time that Gray was thus amusing himself and incidentally making substantial contributions to electrical knowledge, Charles Cisternay du Fay, a young Frenchman at the Court of Louis XV, was making equally noteworthy progress. As Hauksbee had done, he first showed that the metals could be electrified as readily as the "electrics" if they were placed on insulating blocks of pitch, so that the charge could not escape. Most important, however, he discovered the two different kinds of electrification and the law of attraction and repulsion. Many previous experimenters had discovered that when a bit of light material is electrified by contact with another body it is at once repelled. It was not clear, however, under just what conditions this repulsion occurs. Du Fay proceeded to investigate the matter and reported his discovery as follows:

> "This Principle is that there are two distinct Electricities, very different from one another; one of which I call *vitreous* Electricity, and the other *resinous* Electricity. The first is that of Glass, Rock-Crystal, Precious Stones, Hair of Animals, Wool and many other bodies. The second is that of Amber, Copal, Gum-Lack, Silk, Thread, Paper and a vast Number of other Substances. The characteristic of these two Electricities is that a body of *vitreous* Electricity, for example, repels all such as are of the same Electricity; and on the contrary attracts all those of *resinous* Electricity."

Thus, it became known that like kinds of electricity repel each other and unlike kinds attract. Almost immediately, Benjamin Franklin suggested the names *positive* and *negative* for *vitreous* and *resinous* electricities, respectively, a nomenclature which has continued to the present day.

Du Fay performed many novel experiments. Suspending himself by silk cords, after the fashion established by Gray, he electrified himself and then observed that when another person came near a discharge accompanied by a prickling sensation and a crackling noise issued from his body. In the dark, these discharges appeared as sparks of fire. Priestley makes the following note in his *History of Electricity*, "The Abbé Nollet says he shall never forget the surprise which the first electrical spark which was ever drawn from human body excited, both in Mr. du Fay and in himself." Du Fay also put forth a two-fluid theory of electricity, soon superseded, however, by Franklin's more simple and plausible one-fluid theory.

In Germany, Professor George Bose was building the most powerful electric machine of his time. With it, he was able to generate a continuous supply of electricity and on one occasion passed a shock through twenty soldiers in a line. It is also said of him that he wished he might die of electric shock so as to provide material for an article for the memoirs of the French Academy of Sciences. Once when giving a banquet to a number of friends, Bose electrified his dinner table, which he had insulated by placing it on blocks of pitch. As the guests approached, jets of fire leaped from the silver, glass and viands. Then the host proceeded to introduce a beautiful young woman, also mysteriously connected with the electric machine and insulated from the floor. It is related that as each guest touched her finger-tips, he received a shock that "made him reel."

Shortly after, Doctor Ludolff, a fellow-countryman of Bose, in a public demonstration ignited ether with the spark from an electrified rod, and then gunpowder was exploded in the same manner. Popular interest became intense, and new wonders were eagerly anticipated.

THE LEYDEN JAR

Famous in the subsequent early history of electricity was the Leyden jar, invented simultaneously by a German, Von Kleist, and the Dutchman, Pieter van Musschenbroek, a professor at the University of Leyden. This device utilized the fundamental phenomenon of induction, first observed by Stephen Gray in 1729. Van Musschenbroek's experiment came about in this way. He was trying to electrify water in a bottle. A gun-barrel had been suspended by silk threads and connected at one end with an electric machine. From the other end, a wire extended downward and dipped into a bottle of water. While the machine was in operation, a friend grasped the bottle with one hand and took hold of the wire with the other. The result was a shock that shook his body "as by a lightning stroke." Van Musschenbroek also tried the experiment and then wrote to Réaumur "that he would not take another shock for the kingdom of France." This was in 1746, and Von Kleist had made a similar demonstration the year before.

The fame of this exploit soon spread, and repetitions of it were the order of the day. The Abbé Nollet stood the Carthusian monks of a Paris convent in a circular line nine hundred feet long, having their hands joined by pieces of iron wire. Then through their bodies he discharged a Leyden jar, whereupon these dignitaries jumped in unison. In the presence of the King, he passed a discharge through one hundred and eighty guards. With this imitation lightning, birds and other small animals were electrocuted. Franklin killed a turkey with a battery of ten Leyden jars. The discharge was passed through water and across rivers and lakes of considerable width. Needles were magnetized with it and fine wires melted.

The Leyden jar was the world's first electrical condenser. In a short time, tinfoil coatings were substituted for the water *in* the bottle and the operator's hand on the *outside*. If you are not familiar with this piece of apparatus from high-school experience, imagine a glass jar about the size of a fruit jar with tinfoil coatings on both outside and inside and extending about two-thirds of the way up the sides. A top of insulating material carries a brass knob and rod, from which a brass chain drops down to the inner tinfoil. To charge the jar, the knob is connected with one terminal of the electric machine, say the positive one, and the outer tinfoil is placed in connection with the earth. As the machine is operated, the inner tinfoil of the jar becomes positively charged, while the outer tinfoil receives a negative charge. When the jar is charged, the connection with the machine is broken, and to discharge it one end of a bent brass rod provided with an insulating handle is placed in contact with the outer foil while the other end of the rod is brought near to the brass knob of the jar. The difference of electrical potential between the two points breaks down the resistance of the air space, and a brilliant flash results.

This charging of the jar is by the method of induction. In the old parlance, the positive charge on the inside of the jar, acting through the glass wall, repels an equal quantity of positive electricity from the outer tinfoil to the earth and holds bound in its place a similar quantity of negative electricity. Thus a difference of potential is established between the two sides of the jar. Then, for instance, when one or more individuals make connection between the outer foil and the knob, the discharge and consequent shock follow forthwith.

At this point, let us digress for a moment to state that the sort of electricity with which we are here dealing is static electricity, or electricity at rest, as distinguished from current electricity, or electricity in motion. The former is now chiefly of historic interest, although the radio operator, so frequently disturbed by the "static" of the atmosphere, would hardly agree with this. We mean, however, that the big achievements in the electrical field are largely with current electricity.

Many examples of static electricity abound. Who has not received a slight shock as he has walked across a rug in wintertime and then brought his hand near to a metal doorknob, light-fixture or bed-post? Gas jets may easily be lighted in this way. The friction of the feet on the rug has charged the body and an opposite charge has been induced in the near-by metal. When the intervening air space has become small enough, a spark leaps across. Or on a winter's evening, possibly you have amused yourself by rubbing the hands briskly together and then with an extended finger lightly touching the fur of the house cat as she lay curled on the rug before the fire. You observed the fur start and the cat gave a twitch. You have noticed too, that a hard rubber comb after use will pick up bits of paper or other light material. These were the sort of experiments with which the early discoveries in electricity were made. If we did not have the record of the past, we should wonder about them as much as did earlier peoples.

AN ECHO FROM AMERICA

Thus far no voice from America has been heard. But at this particular point in the progress of things electrical, Benjamin Franklin was to focus the attention of the scientific world upon his exploits. Chancing to see some electrical experiments in Boston, made by a Doctor Spence from Scotland, he began to experiment for himself. In 1747, in speaking of this, he says, "I never was before engaged in any study that so totally engaged my attention and my time as this has lately done." At his home in Philadelphia, he gathered about him a small group of interested investigators, probably the first scientific gathering in the New World.

One of Franklin's earliest discoveries, he describes as the "wonderful effect of pointed bodies, both in drawing on and throwing off the electrical fire." Others had noticed this, but Franklin was the first to understand its importance and to put it to practical use. This fact that metal points will draw electricity from a charged body led in due time to his invention of the lightning-rod. However, this first practical application of electrical phenomena to be made anywhere in the world was preceded by his famous experiment with the kite, whereby he forever robbed the lightning of its mystery and identified this manifestation of "Divine wrath" with the electricity of the Leyden jar.

Franklin, too, discovered that the charges in a Leyden jar reside, not on the tinfoil coatings, but on the glass walls which separate them. The glass itself became known as the dielectric. This quaint printer of the Quaker City also changed the form of the condenser, using a series of glass plates separated by two sets of tinfoil, thus making this instrument essentially the same as it is to-day. We have already noted that Franklin gave the names *positive* and *negative* and put forth the one-fluid theory of electricity, which was universally accepted until the coming of Faraday and Maxwell.

In this theory of Franklin's, he "regarded a positive charge as indicating an excess, a negative charge a deficiency, in a certain normal amount of an all-pervading electrical fluid." Although entirely arbitrary and purely an assumption, this theory beautifully accounted for electrical phenomena. It was good enough until something better came. At this point, let it be briefly stated, however, that in the light of the modern electron theory, a body negatively charged is believed to possess an excess of electrons, while a positively charged body has lost its normal quota of these units of subatomic structure, therefore having a deficiency. In a neutral body, the sum of the positive charges on the nuclei of the atoms is exactly balanced by the planetary electrons. When, for instance, we charge a glass rod positively by rubbing it with silk, we remove some of the negatively charged electrons, thereby leaving a deficiency. At the same time, of course, the silk receives an excess of electrons and becomes charged negatively. It can at once be seen that, if we substitute electrons for Franklin's hypothetical fluid, there is little difference superficially in the two theories. However, one is a theory of convenience; the other is based upon known experimental facts. A current of electricity is believed to be a flow of electrons along a conductor. H. A. Rowland a half-century ago showed that a moving charge of static electricity behaves like an electric current, a point to which we shall refer again. It may be added that as to the ultimate nature of electricity we are yet as much in the dark as ever. Like gravitation, it is an elemental fact of Nature, which must be accepted and not explained, except in a wholly empirical way.

Before leaving Franklin, let us have a word about lightning. It is believed that water vapor leaves the surface from which it is formed positively charged, that is, it contains a deficiency of electrons. When the vapor condenses, the charge distributes itself on the surface of the droplets of water. A large mass of these, as in a cloud, gives a very large aggregate charge, which induces in an adjacent cloud or in the earth beneath an opposite charge. When the difference of potential becomes great enough, the insulation of the air breaks down and we have the lightning flash, which simply consists in heating the particles of dust and molecules of air to incandescence. This discharge of electricity, too, parts the air, and when it comes together again the impact of the molecules produces sound waves, giving rise to thunder.

The advantage in Franklin's lightning-rod is due to the fact that points serve to draw off the charge from a cloud quietly and conduct it to the earth, thereby reducing the difference of potential below the point at which lightning will occur.

That lightning produces magnetic effects has been known for two centuries. The *Philosophical Transactions* of London in 1735 reported that a merchant named Wakefield, ". . . having put up a great number of knives and forks in a large box, and having placed the box in the corner of a large room, there happened in July, 1731, a sudden storm of thunder, lightning, etc., by which the corner of the room was damaged, the box split, and a good many knives and forks melted, the sheaths being untouched. The owner emptying the box upon a Counter where some Nails lay, the Persons who took up the knives that lay upon the Nails, observed that the knives took up the Nails." It was known, too, that the magnetic needle is often affected in a thunderstorm. Here was the foreshadowing of a discovery which in the following century was to mark a turning-point in the progress of electricity. However, a whole new array of electrical phenomena first had to be brought to light, and to these researches we shall now turn.

VOLTAIC ELECTRICITY

Near the close of the eighteenth century, practical electricity had to its credit only the lightning-rod. It was still the plaything of science, of tremendous popular interest, with new discoveries following close upon one another, but with no important applications. Then, in the year 1793, came a fundamental discovery—one which was to usher in a new era and to serve as a stepping-stone to a still greater triumph. It hinges upon the story of Galvani and the frog's legs.

Luigi Galvani, a distinguished professor of anatomy at the University of Bologna, Italy, had become much interested in animal electricity. One day in 1791, he placed a dissected frog on a table near an electrical machine. Without knowing it, he was about to become the chief actor at one of those strategic moments which occasionally punctuates the drama of scientific discovery. Presently, as an assistant lightly touched the nerves of the frog's leg with the point of a knife, Galvani in astonishment observed that the muscles were thrown into vigorous contraction. Beginning a thorough investigation of all the circumstances attending this remarkable manifestation, Galvani soon discovered that the twitching occurred only at the instant when a spark was drawn from the electric machine. He says: "The phenomena happened exactly as before. Strong contractions took place in every muscle of the limb, and at the very moment when the sparks appeared."

Curious to know whether lightning would produce similar effects, Galvani erected a metallic conductor on the highest portion of his house and connected it with his laboratory below. Then he waited for a thunderstorm. As he saw it approaching, he attached a dissected frog to the conductor and connected the feet to a wire, which he allowed to dip into the water of a near-by well. Galvani says: "The results came about as we wished. As often as the lightning broke forth, the muscles were thrown into repeated violent convulsions, so that always, as the lightning lightened the sky, the muscle contractions and movements preceded the thunder and, as it were, announced its coming. It was best, however, when the lightning was strong or the clouds from which it broke forth were near the place of the experiment."

Still, this Italian professor had only made a beginning. He continued his experiments for a number of years, desiring, as he said, to know the effects from "the daily quiet electricity of the atmosphere." For this purpose, he impaled several frogs on brass hooks passing through their spinal columns and hung them from an iron railing. During a thunderstorm the contractions occurred as before, and occasionally out of a clear sky. Then, abandoning outdoor experiments, he transferred the frogs to his laboratory. There, he discovered that when one of the frogs was placed on a metallic plate and the hook piercing his spinal column was brought in contact with the plate, the twitching occurred. For the metal plate, he substituted glass, and the effect disappeared. However, he found that, if while the frog rested on the glass plate, he touched both a nerve and a muscle with a bent rod, consisting of two different metals, prolonged convulsions followed.

In those simple experiments, Galvani had produced the first cell for generating current electricity in history. You have done the same thing, when a fresh silver filling in one tooth may have come into contact with a gold filling in a tooth above or below it. The saliva, acting upon one of these metals and not the other, sets the nerve tingling with a tiny electric current. Galvani had brought about similar conditions. There were two different metals moistened by the saline juices of the frog's body. The resulting chemical action produced an electric current.

Galvani had now made his contribution, the essential step necessary to further discovery, and for it we honor his memory in the expression "galvanic current." More important, his work inspired his countryman, Alessandro Volta, to make investigations which led to the practical electric cell and a new type of electricity. Born within three years of the first centennial of Galileo's death and Newton's birth and dying just one hundred years after the latter's death, Volta was for thirty years professor of physics at the gymnasium in his native town of Como and at the University of Pavia.

Learning of Galvani's discoveries, Volta began to experiment along similar lines. He had already invented the electrophorus, a device for obtaining an electric charge by induction. Holding a silver coin and a gold coin against the tongue, he found that a bitter taste was experienced if the coins were connected with a wire. Here was Galvani's experiment in a different form. Placing one end of a bent rod made from two different metals in the mouth and touching the eye with the other, he reported a sensation of light at the moment of contact. To that of motion, Volta had added those of taste and sight as effects of the new form of energy. Then, he proceeded to show that, contrary to the opinion expressed by Galvani, the nerve of the frog was not an essential part of the circuit. By means of a delicate electroscope and a condenser, he proved that when two metals, such as zinc and copper, are placed on insulating supports, they will exhibit electric charges after having been brought together for an instant and then separated. Contact of metals seemed to give electric charges, and Volta declared that galvanic electricity might as well be called "metallic" as "animal." He began his experiments in 1793, but did not announce them until 1800.

In that year, Volta sent to Joseph Banks, President of the Royal Society of London, a letter telling of his discoveries and giving an account of his newly invented "Voltaic pile." This consisted of a series of alternate copper and zinc plates, separated by pieces of blotting-paper or flannel moistened with water or brine. When the copper plates, joined to one terminal, were connected in external circuit with the zinc plates, joined to another terminal, a current of electricity flowed. In this letter, Volta also described his famous "crown of cups." A series of cups containing dilute acid or brine were connected by bent strips of copper and zinc, one end of each strip dipping into the solutions in adjacent cups. We should call this now a number of cells grouped in series.

Volta had taken the discovery of his countryman, shrouded in mystery, and given to it meaning. In his hands it brought a great scientific triumph. Thenceforth, voltaic, or current, electricity was to assume the leading rôle. Enthusiasm eclipsed all previous records. Every one was set on edge for new developments. As Davy said, "The voltaic battery was an alarm bell to experimenters in every part of Europe." Within six weeks of the receipt of Volta's letter, the first "pile" was constructed in England, and with it William Nicholson and Sir Anthony Carlisle, on May 2, 1800, decomposed water with the electric current. This event may be regarded as laying the foundation of the vast electrochemical industry of to-day.

Honors were now showered upon the modest physicist from Pavia. Napoleon called him to Paris to demonstrate before the Institute. Voltaire invited him to his home near Geneva. The Royal Society of London had already elected him to membership, and the French Academy now did. In 1881, an international congress of engineers meeting in Paris named in his honor the unit of electromotive force, and in 1927 a similar congress of physicists at Como, Italy, observed the centennial of his death.

The wonders of electricity now became the topic of the hour. It was the fashion for ladies and gentlemen to attend lectures on electricity and to support laboratories. Every scientific man of importance equipped himself with a static machine and Leyden jars. Makers of apparatus did a thriving business in providing the public with various electrical devices. And there were not lacking at country fairs and elsewhere crafty gentlemen to separate the peasantry from their spare change by giving demonstrations of this mysterious manifestation of energy.

The first brilliant triumph with the newly discovered electric current belongs to Davy. He showed that water consists by volume of two parts of hydrogen to one of oxygen, but more important was his discovery of half a dozen new elements, glory enough nowadays for as many lifetimes. With a voltaic battery of two hundred and fifty cells, he decomposed potash, obtaining the metal potassium. It is said that, as the globules of molten metal began to appear at the negative pole of his apparatus, Davy was so overcome with joy that he danced about the laboratory like a madman, leaving the completion of the experiment to an assistant. Be that as it may, he quickly followed this discovery by the separation in like manner of the metals sodium, calcium, barium, strontium and magnesium. With a battery of two thousand cells, he produced the first arc-light in history and a temperature rivaling that of the sun. In it, he melted the most refractory substances, such as platinum, quartz, sapphire and magnesia.

At last this subtle manifestation of energy had been put to work. It was on the highway to accomplishments of vast import and a field of research which even yet stretches far away into the dim distant future.

The fundamental principle underlying the operation of the voltaic cell is the unequal chemical action of a solution —acid, alkaline or saline—upon two elements. The solution may act upon one element and not upon the other, or more rapidly upon one than upon the other, or the action may be quite different in character upon the two, as in the two-fluid cell so much used in the early days of telegraphy.

FROM OERSTED TO FARADAY

Twenty years slipped by following Volta's memorable announcement, and then came a discovery equally momentous. Davy's work had been of the utmost importance, but it marked no new departure of fundamental significance in the growth of the science. Useful as battery currents are for a multitude of purposes, it can be readily seen that they never would have brought the Age of Electricity. To bridge the gap from the voltaic cell to the dynamo more knowledge was needed, and in due time it came. Like many another similar turning-point in the progress of science, it resulted from a chance observation, but one which fell into fertile soil. In 1819, Hans Christian Oersted, of the University of Copenhagen, made a discovery which founded the science of electromagnetism.

Many had noted similarities between electricity and magnetism, but current electricity was nearly a quarter of a century old and no direct kinship had been discovered. Then, at the close of one of his lectures in 1819, Oersted, in a moment of inspiration, placed the wire from a heavy galvanic battery over and parallel with a compass needle upon his desk. He was amazed to see the needle swing through a large arc and place itself at right angles to the wire. He reversed the direction of the current, and the needle promptly swung to the opposite side. Soon he had made the test in every possible way, and always the needle was affected. An eye witness, Christopher Hansteen, says: "Thus the great detection was made; and it has been said, not without reason, that 'he tumbled over it by accident.' He had not before any more idea than any other person that the force should be transversal. But as Lagrange has said of Newton on a similar occasion: 'Such accidents only meet persons who deserve them.' Professor Oersted was a man of genius, but he was a very unhappy experimenter; he could not manipulate instruments. He must always have an assistant, or one of his auditors who had easy hands, to arrange the experiment; I have often in this way assisted him as his auditor."

Oersted now proceeded to see whether he could cut off this influence. Between the needle and the wire carrying the current, he placed all sorts of materials, but concluded that the influence "acts upon the needle through glass, metals, wood, water, resin, earthen jars, stones; for when we placed between the two a plate of glass, or of metal, or a board, the result was not cancelled; indeed all three combined hardly lessened the effect."

What Oersted had done was to demonstrate that a conductor bearing an electric current possesses a magnetic field. Otherwise, the compass needle would not have been affected.

In June of the following year he announced his discovery, and soon it was being repeated everywhere. Here was an experimental fact, wholly new and of the utmost significance. Whither would it lead? That was the question being asked on every hand.

A number of men now took up the search. Dominique François Jean Arago, distinguished astronomer and physicist of Paris, almost immediately contributed the experimental fact that iron filings are attracted by the current. Davy proved that this is because each little particle of iron becomes a magnet, one particle attracting another so as to form a ring about the wire. This showed, too, that the magnetizing force is exerted in a plane at right angles to the wire. Bit by bit the structure grew.

The most notable follower of Oersted was André Marie Ampère. In his personality and life, there is much to remind one of Thomas Young. Gifted, precocious, mastering Latin at the age of twelve that he might thereby gain access to the science of mathematics, working all the difficult problems in Laplace's *Méchanique Céleste* at eighteen and widely read in many fields, the youth gave promise of a distinguished career. The beheading of his father in the Revolution gave him a shock which for a time crushed him mentally, but the reading of Rousseau's work on botany aroused him from his mental stupor, and he threw himself into scientific pursuits with vigor. The loss of his young wife a few years later once more precipitated him into a period of depression and melancholy. He taught chemistry and physics in his own town of Lyons and later became a professor in the Polytechnic School in Paris.

In September, 1820, not quite three months after Oersted's announcement, a member of the Institute of France appeared before that body with the news of the great discovery. Among the most interested listeners was Ampère. Immediately, he repeated the experiment with every conceivable variation. For the first time, he formulated the laws governing the deflection of the needle when under the influence of an electric current. At the end of a week, he went before the Institute with the results of his investigations. Then he began to experiment to find the effects of two parallel electric currents upon each other, for he argued that, since one current acts like a magnet, two currents should act in a similar way. And so they did. Soon he had discovered the laws with respect to the attraction and repulsion of such currents in all cases.

Ampère also put forth the hypothesis that the molecules themselves are magnets, a view which is still held. Furthermore, he believed that the magnetism is due to an electric current which perpetually flows in a closed circuit within the molecule. In 1823, he published a paper setting forth a mathematical theory of the facts of electromagnetism, which Maxwell a generation later pronounced to be "perfect in form and unassailable in accuracy." In his honor, we have designated the unit of the electric current as the *ampere.*

To keep the record straight, let us state at this point a discovery which should have been given before. Charles A. Coulomb, of France, had already shown that Newton's law of inverse squares holds for electric and magnetic attractions and repulsions. He also proved that two like charges of static electricity repel each other with a force which is proportional to the quantities of electricity involved. Here was something quite similar to gravitation, but the semblance went no further. There is no known identity between gravitation and electricity.

Surely, the science of electricity was gaining momentum. Although no definite units of current strength and electrical pressure had been formulated, these quantities were clearly recognized. Something more was needed. What governs the relation between the quantity of current and the pressure that makes it flow? There must be some factor in the flow of electricity analogous to the flow of water in a pipe. The amount of water which a pipe will deliver depends upon the head, or pressure, and the resistance offered by the pipe. Was there not something in an electric circuit corresponding to the resistance of the pipe? This was the question which Georg Simon Ohm asked himself, and his solution of it constituted another link in the chain of electrical progress.

It is said that once when Edison was on the witness stand, a lawyer asked, "Mr. Edison, what is Ohm's Law?" Edison replied, "I do not know, sir. Ohm's Law contains essentially the whole of electrical engineering; and I am not familiar with the whole of that subject."

Ohm's life was one of contrasts and much adversity. His father, a master locksmith, intended that his two sons should follow his calling, but their unusual aptitude for science and mathematics brought a change of plans and three terms of training at the German University of Erlangen in their native town. By private tutoring, Ohm earned sufficient funds to complete his university course, and obtained a teaching position in Bamberg. Soon, however, the school was closed, and the young teacher could not secure another appointment. Discouraged, he returned to the bench in his father's shop. In 1817, an essay on geometry, "written in a room without a fire," brought him a post as teacher of mathematics and physics in the Jesuit High School at Cologne. But he wished to be more than a teacher. His ambition was to do experimental work and some day to become a university professor. Hampered by poverty, lacking both facilities and apparatus for research work and out of touch with other scientists, the process was a slow one. Still, his mechanical skill, acquired in his father's shop, and an invincible determination brought results.

About this time, Joseph Fourier had published a treatise on heat conductivity of materials, in which he had worked out a relationship between the flow of heat through a conductor and the fall in temperature. This set Ohm to thinking that there might be some similar connection in the flow of electricity through a wire. In his spare time, he began to experiment along these lines. At length, by actual measurement, he had obtained a series of numbers representing the relative degrees of conductivity of nine different metals. In his initial table, he found copper to be a better conductor than silver, but discovered his mistake and corrected it. Out of these measurements emerged the new quantity of electrical resistance and the fact that this resistance, in the case of any given conductor, increases with the length and decreases as the area of the cross section of the wire becomes larger. The three quantities of current flow, electrical pressure and resistance, he connected in a simple numerical relationship, known as Ohm's Law.

Having in this work difficulty with his batteries, Ohm was led to make use of a discovery of the Prussian scientist, Thomas Johann Seebeck, who had found that two metals, such as copper and bismuth, will produce a difference of potential, if the metals are joined together and heated at the juncture. In this way he obtained a better current for his purpose, and incidentally made use of an electrical effect which has since become of great importance.

Ohm now obtained a year's leave of absence from his position and went to Berlin to prepare a book setting forth his discoveries, fondly cherishing the hope that this would bring recognition and the coveted university appointment. However, the effect, strange to say, was just the opposite. It did not appear from his book that his results were obtained by experiment, and his contemporaries resented what they regarded as merely theoretical conclusions. One critic referred to Ohm's theory as "a web of naked fancies." Bitterly disappointed, he returned to Cologne, where he had labored for nine years as it now seemed for naught. Even there, misfortune pursued him. Ill-advised criticism of his work reached the Minister of Education, who forthwith announced that "a physicist who professed such heresies was unworthy to teach science."

Ohm resigned his position and for six years tutored at a meager income. Then, the tide turned. Recognition came, first from abroad and then from his own country. In 1833, he received an appointment in the Nuremberg Polytechnic School in Bavaria, and seven years later the Royal Society of London conferred upon him the Copley Medal in honor of the very researches for which he had been so severely censured. The truth had become known, and his discoveries were found to be of the utmost practical value. In 1849, the long-wished-for university professorship came. Five years later, he died. In 1881, the International Congress of Electricians, assembled in Paris, honored his memory by naming the unit of electrical resistance the *ohm.*

In the meantime, the electromagnet, fundamental to a host of electrical appliances and to the subsequent development of the dynamo, had been invented. Arago had pointed out the increased magnetizing power of a spiral conductor over a straight one, and Ampère had shown that such a spiral acts like a magnet. By thrusting a bar of steel inside a large number of turns of wire, called a solenoid, he was able to magnetize it with great success. When he substituted soft iron for the steel, he found the iron strongly magnetized as long as the current flowed, but instantly demagnetized when the circuit was broken. To this device, Ampère gave the name electromagnet. Then, in 1825, William Sturgeon, a self-taught scientist of Lancashire, wrapped eighteen turns of bare copper wire about a horseshoe-shaped piece of soft iron, having first covered the iron with varnish for insulation. Through the wire, he passed a current from a single copper-zinc cell and was able to lift a weight of nine pounds. This was the first demonstration of the lifting power of an electromagnet. A far cry it was to the huge lifting magnets of to-day, but a big beginning. In a short time, this device was to become the basis for the invention of the telegraph, the first commercialization of the electric current.

Evidently, the success of the electromagnet depends upon the ease with which soft iron is magnetized and demagnetized. That is, it exhibits temporary magnetism only, whereas steel once magnetized retains its power of attraction for a long time. It was discovered early, however, that jarring or heating will largely demagnetize a magnet. Furthermore, a piece of steel heated red hot can not be picked up by a magnet. It became known, too, that in the magnetizing of steel a saturation point is reached, beyond which the process ceases. These and similar effects led to the theory of molecular magnetism, in which each molecule is regarded as a tiny magnet, having a north pole and a south pole. In an unmagnetized piece of iron or steel, the molecular magnets are arranged hit-and-miss fashion, forming multitudes of closed rings with the north pole of one close to the south pole of another. Within the magnet are thus myriads of closed magnetic circuits, but no magnetism manifests itself on the outside. When, however, the iron or steel is brought into a strong magnetic field, hosts of these molecular magnets are lined up, with their north poles pointing in one direction and their south poles in the other. Saturation is obtained when this process has reached a maximum. It is now easy to see why jarring or heating weakens the magnetic force. The vibration causes the molecules to swing back into the closed ring grouping. A red-hot piece of steel can not be attracted by a magnet, because its molecules are in a too rapid state of vibration to maintain a consistent line formation. An electromagnet loses its magnetism when the circuit is broken, because molecules of soft iron will not "stay put" except under the influence of a strong external force. They are like a lot of unruly schoolboys, who will observe order only when under the influence of stern discipline.

Another evidence of this theory is the fact that when a magnet is broken, two magnets are formed, with opposite poles on either side of the break. Presumably, if this division could be carried to a molecular state, the same result would be obtained. The soft-iron core of a transformer is magnetized by an alternating current, which reverses its direction one hundred and twenty times a second, giving rise to a low-pitched hum, which is attributed to the movement of the molecules in rapidly changing end, for this reversal of the current reverses the magnetic polarity at the same rate. Delicate measurements show, too, that a bar of steel is slightly longer when magnetized than when demagnetized. J. A. Ewing, of the University of Cambridge, also showed that a model consisting of a large number of small pivoted compass needles will exhibit in the presence of an external magnetic field all the phenomena of magnetism. The compass needles correspond to the molecular magnets of iron and steel.

Developments of the utmost importance were these following Oersted's discovery of 1819. Slowly the secrets of Nature were yielding their meanings before the attacks of many minds. The ground was being broken, and the world was ready for the next great advance.

THE DISCOVERIES OF FARADAY

When you press a button and flood the room with light, or turn a switch and start a motor or tune your radio set for the reception of the voices and music that fill the ether, you are harking back to the discoveries of Michael Faraday, the greatest scientific investigator of the nineteenth century. Upon the fundamental researches which he made rests the whole superstructure of this modern age of electricity with its superpower plants, its long-distance transmission lines, its "Great White Ways," its motor-driven machinery, its telephones and radios and an atmosphere that fairly tingles with electromagnetic vibrations. Had not Faraday or some one else made the basic discoveries underlying all this, we should stand to-day in respect to things electrical where our forefathers stood a century ago.

And when we contemplate the electrical progress of a century, I think we are inclined to agree with Huxley when he said, "I weigh my words when I say that if the nation could purchase a potential Watt, or Davy, or Faraday, at the cost of a hundred thousand pounds down, he would be dirt cheap at the money. It is a mere common-place and everyday piece of knowledge that what these men did has produced untold millions of wealth in the narrowest economical sense of the word."

And yet Faraday died a poor man. His salary as Director of the Royal Institution, in which he spent nearly half a century as a pure researcher, was only one hundred pounds a year, plus lodgings, fuel and light. In 1830, when his work had made him famous, he made more than a thousand pounds from private fees. Wealth was at his command. The world was clamoring for his services. Huxley estimated that he might easily have amassed a fortune of nearly a million dollars, had he chosen to commercialize his genius. In the year 1831, he reached the parting of the ways. He had to choose whether he would sell his services for private gain, or devote his life to original discovery—pure research, we call it. He could not serve two masters. The record of his private income tells the decision. In the following year, it had dropped to a very modest sum, and by 1838 it had reached the vanishing point. But, as Tyndall said, "his was the glory of holding aloft among the nations the scientific name of England for a period of forty years."

Born of humble parentage, reared in poverty, receiving only the rudiments of an education and apprenticed to a bookbinder—there was little in the early life of Faraday to give promise of a brilliant scientific career. In viewing the events of that period, it seems almost like a chance throw of the wheel of fate that he was salvaged for a life of original discovery. It appears to be equally remarkable, too, that a man with so little educational background and with no mathematical training beyond the most elementary arithmetical processes should have been able to carry on scientific research in the manner of a master. With the exception of Davy, his superior and discoverer, he is one of the very few pioneers in physics who did not possess university training. Such geniuses as were these two noblemen of science come only once or twice in a century.

In his apprentice work as a bookbinder, Faraday did much reading, particularly in the field of science. His brother provided the fee for attendance upon a course of lectures on natural philosophy, given by a Mr. Tatum. More important still, a patron of the bookbindery invited Faraday to hear the last four in a series of lectures being given by Sir Humphry Davy at the Royal Institution. This breath of inspiration crystallized his determination to abandon the life of a tradesman, which was becoming exceedingly distasteful. To be a scientist thenceforth seemed to be the great ambition of his life, and he decided to write to Davy requesting a position. Of this bold decision, he once said:

> "My desire to escape from trade, which I thought vicious and selfish, and to enter into the service of science, which I imagined made its pursuers amiable and liberal, induced me at last to take the bold and simple step of writing to Sir H. Davy, expressing my wishes, and a hope that, if an opportunity came in his way, he would favour my views; at the same time I sent the notes I had taken of his lectures."

That Davy received this request with kindly consideration, the whole world may be grateful. And so one day a carriage drew up before the humble lodgings of the Faradays, and a liveried footman bore a note to the would-be scientist from the great man whose discoveries and lectures were winning for him the acclaim of all London. As a result of this exchange of correspondence, in March, 1813, at the age of twenty-two, Michael Faraday became assistant in the Royal Institution at a salary of twenty-five shillings a week.

A few months later, Faraday accompanied Davy on a two years' tour of the Continent, where he met many distinguished scientists and formed valued friendships. Upon his return, he began to prepare himself by wide reading of the scientific discoveries already made and to carry on investigations of his own, chiefly in the field of chemistry. In 1820, he read his first paper before the Royal Society, and three years later, although in opposition to Davy's wishes, he was elected a Fellow of the Society.

It was in 1821 that Faraday began his series of researches in electromagnetism which in ten years were to bring him to the zenith of his career. His first venture in this field was inspired by a failure of the English physicist, Wollaston, to make a current-bearing conductor rotate about a magnetic pole. In line with Oersted's discovery, both Wollaston and Faraday agreed that, if an electric current will deflect a magnetic needle, the opposite effect ought also to be possible. The solution of the problem, whereby Faraday, in a single piece of apparatus, caused a pivoted bar magnet to rotate about a current-bearing conductor and a pivoted conductor to rotate about a magnet, displayed in a striking way the originality of the investigator. It is said that when Faraday saw the success of his experiment—one magnet revolving about a wire and a second wire revolving about another magnet—he danced around the room, exclaiming, "There they go, there they go!"

At intervals in the succeeding decade, Faraday devoted himself to experiments which were to lead him step by step to the discovery of induced currents, the most fundamental principle in the whole history of electrical progress. In the meantime, in 1825, he was elected Director of the Laboratory of the Institution.

The problem that Faraday set himself to solve was this: if an electric current possesses a magnetic field, why should it not be possible to cause a magnetic field in some way to induce an electric current? As the old saying goes, "It is a poor rule that will not work both ways." Furthermore, the law of action and reaction seemed to demand it.

In his first experiment, he placed a wire through which a current was flowing alongside another wire and connected the second wire to a galvanometer, an invention of J. S. C. Schweigger, of the University of Halle, for the detection of an electric current. It was Faraday's hope that this second wire might also show the presence of a current, but the desired result did not appear. Busy with other work, he did not return to this investigation for three years, when he repeated the experiment without success. Three years more slipped by, and it was not until August, 1831, that he attacked the problem again, and this time victory perched upon his banner.

In every instance during the preceding decade, Faraday had been compelled to write across his note-book "No result," and then within the brief space of only ten days of actual work in the autumn of 1831 we see this persistent knocking at the door of eternal truth unlock for him the secrets of electromagnetism. In that moment, the dynamo, the induction coil, the motor, the transformer, the telephone, the radio and a host of other appliances were potentially born. But, having discovered the underlying principle, having pointed the way, Faraday was content. He turned to other fields, leaving the applications to men of lesser brains. The only reward he sought was the joy of original discovery. Let us see how it came about.

Again, Faraday pondered the problem. He knew that a charge of static electricity would induce an opposite charge in a neighboring conductor; magnetic induction, too, was well known as illustrated in the electromagnet; Oersted had proved that a current-bearing conductor possesses a magnetic field; and Ampère's experiments had led to a knowledge of the attraction or repulsion of two electric fields. These were his facts, and it seemed perfectly logical to assume that magnetism, either from a magnet or from an electric current, should in some way be able to induce another electric current. With Faraday, this extraordinary keenness of insight was a matter of intuition, a faculty characteristic of a number of other men of science, particularly Newton and Maxwell, but which was developed in this second great master of the Royal Institution to an unusual degree.

And so on a soft iron ring six inches in diameter and seven-eighths of an inch thick, one day late in August he wound two coils of wire, winding each on a separate half of the ring. One of these coils, he connected to a battery of ten cells, placing a key in the circuit. The terminals of the other coil, he carried to a galvanometer. When he closed the circuit, he observed a throw of the galvanometer needle, indicating the presence of a momentary current. We say momentary, for immediately following the needle again became stationary, pointing in the usual direction. When the circuit was broken, Faraday noticed a similar deflection, but in the opposite direction. That was all. Not much—meaningless to most of Faraday's contemporaries; very few there were who could interpret it. But it was a revelation for which the world had waited from the day that some caveman rubbed a bit of amber across his furskin coat and thereby awoke the "sleeping soul within." To Faraday, these almost imperceptible "kicks" of the compass needle meant success. His dream had come true. He had at last induced a current, feeble though it was. Had he possessed the vision of a prophet, he might have seen emerging from that simple phenomenon a new world of scientific fact and theory.

Faraday was still somewhat dubious of the importance of his discovery. A month later, he wrote, "I am busy just now again on electro-magnetism, and think I have got a hold of a good thing, but can't say. It may be a weed instead of a fish that, after all my labour, I may at last pull up."

He now substituted for the iron ring one of copper, a non-magnetic material. He produced the effect as before, but it was greatly reduced. Still, the new electrical law was operating there, just as in the earlier experiment. His next step was to induce a current in a coil of wire merely by the movement of a permanent steel magnet in its vicinity. The throw of the needle occurred as before. There could no longer be any question of the conversion of magnetism into electricity.

Another variation was then introduced. Faraday wound two lengths of copper wire, each two hundred and three feet long, on a wooden bobbin, one over the other. As in his first experiment, he connected one wire through a battery of ten cells and a key, while the other was carried to the galvanometer. On making and breaking the primary circuit, the one in which the battery was placed, there were the kicks of the needle as in the other cases.

One thing now became clear: a current is induced in a conductor only at the instant that the current in the primary changes—when it is made or when it is broken. For the needle showed no deflection when the current was steadily flowing in the primary circuit. Step by step, Faraday was arriving at fundamentals. He began to suspect that it is a varying magnetic field cutting across a conductor that induces the current. To confirm this, he connected a coil of wire in the form of a solenoid to a galvanometer. Then, he suddenly thrust a bar magnet into the coil and produced a throw of the needle. When the magnet became stationary, the needle came to rest, but when he removed it, there was the throw in the opposite direction.

One of his most beautiful experiments and a new link in his chain of evidence was a demonstration of what had been long believed, namely, that the earth itself is a huge magnet. By rotating in the earth's field a copper coil, the terminals of which were connected to his galvanometer, he again obtained the evidence of an induced current. Thus, the conclusions of Peregrinus and Gilbert had found experimental confirmation of the most convincing sort.

Faraday now proceeded to a modification of an experiment performed by Arago a decade before. Arago had rapidly rotated a copper disk beneath a mounted compass needle, and was perplexed to discover that the needle rotated too. Why, he could not explain, and neither could any one else. Faraday rotated a copper disk, mounted on an axle, grindstone fashion, between the poles of a large horseshoe magnet, a magnet which is still on exhibition in the house of the Royal Society. He connected the axle with one terminal of a galvanometer and, as the disk was rotated, he held a wire from the other terminal against the edge of the disk. The needle was deflected as usual, but this time steadily in one direction. When he reversed the direction of rotation, the deflection of the needle was also reversed. Here was the world's first dynamo.

It now became clear that the rotation of the copper disk in both cases induced a current by its movement through a magnetic field. In the experiment performed by Arago, it was seen that the field of the induced current acted upon that of the compass needle to produce motion. That is, there were attraction and repulsion in such a way as to drive the needle about.

This latter fact foreshadowed a law formulated a little later by a Russian physicist, Lenz, and stated as follows: "*The field of an induced current is always such as to oppose the field or motion that induces it.*" That is, we can not get something for nothing. There is always opposition. Were this not true, we should be creating energy—getting something better than perpetual motion.

Faraday now went a step further. He showed that any variation in the strength of a magnetic field will induce a current in a neighboring conductor. He demonstrated this beautifully with an electromagnet, whose strength he was able to alter at will. Each increase or decrease of the magnetic field manifested itself in a corresponding variation in the deflection of the needle.

The chain of experimental evidence was now complete, but before we state the law let us consider another conception invented by Faraday. "Action at a distance," assumed by French mathematicians in dealing with magnetic and electrical phenomena, was always repugnant to Faraday. With his vivid imagination such action did not appeal to him. Furthermore, he was not a mathematician. He could not use that language. He must have a substitute, and therefore he was led to the idea of "lines of force."

It is well known that iron filings sprinkled on a piece of paper laid over a magnet will arrange themselves in a series of beautiful curves, each of which seems to emanate from one point of the magnet and reenter at another. Any point on one of these lines lies in the direction of the field at that point. If a small compass needle is placed in a magnetic field, it will set itself along one of these lines. In fact, a magnetic line of force is sometimes defined as the path which a north pole, free to move, will take in being repelled from the north pole of a magnet to the south pole. That is, the medium in the vicinity of a magnet seems to be permeated with lines of influence.

Another series of experimental facts also confirmed Faraday in this conception. In the case of static electricity, electric charges were supposed to attract and repel one another at a distance without being influenced in any way by the intervening medium. Furthermore, these attractions and repulsions were regarded as taking place along straight lines. Faraday questioned both and began to experiment. For the medium between the inner and outer surfaces of a Leyden jar, he coined the name "dielectric," and he devised what was virtually such a jar in which the dielectric could be changed. It consisted of two concentric metal spheres with a hollow space between, which could be filled with any desired material. Then, taking air as a standard in determining the degree of electrostatic induction between the two spheres, he found that this effect varies with the substance used in the intervening space, being much stronger with other substances than with air. That is, electrostatic induction is affected by the nature of the dielectric. Faraday called this fact "specific inductive capacity." However, we should note that Sir Henry Cavendish had also made this same discovery many years before, but of this Faraday was wholly ignorant. He, too, satisfied himself by experiments that induction often takes place in curved lines.

Fortified with this experimental evidence, Faraday now elaborated his idea of lines of force. In some way the medium about a magnet or in the vicinity of an electrostatic charge seemed to be modified—to be in a state of strain. Faraday conceived of multitudes of lines of action, or force, in every plane. He thought of these lines as having the property of shortening in the direction of their length and of mutual repulsion at right angles. Thus, he pictured stresses and pressures in his field of force. With this conception, he was able to visualize and explain much of magnetic and electrical phenomena. It proved to be of immense assistance to himself and other workers.

Now let us return to the law of induced currents. It may be stated thus: "*Whenever a conductor cuts lines of force or lines of force cut a conductor, an electromotive force is induced.*" That is, a difference of electrical potential, or pressure, is set up, and if this occurs in a closed circuit, a current will flow. For instance, the armature of a dynamo may be turned through the field of force, but if there is no external circuit, only an electromotive force will be developed. No current will flow. It was now clear why Faraday had obtained a throw of the needle only when the circuit had been made or broken or when his magnet was in motion. Lines of force at rest with respect to a conductor induce no current. Motion is essential. Work must be done.

The discovery had now been made—certainly the most important of the nineteenth century in the field of electricity, possibly the most important of all time. Still, only a few could see its significance. Faraday himself by no means had more than a faint picture of the vast tide of scientific and industrial progress which would take its rise from this new advance. And yet he knew that he had unearthed a fundamental fact of Nature of the utmost value. To the non-scientific man, however, it had little meaning. Gladstone on one occasion, having witnessed one of Faraday's demonstrations of a new discovery, asked of what use it might be, to which Faraday replied, "Why, sir, you will soon be able to tax it."

The year 1831 marked Faraday's most brilliant period of discovery, but in the remaining thirty-six years of his life he added much to the fund of scientific knowledge. He now proceeded to show that he could obtain with the electricity of his static machine all the effects observed with the current electricity of the voltaic battery, thereby establishing their fundamental identity. In one of his most notable researches, he discovered and formulated the laws of electrochemical action, introducing a system of nomenclature which has remained standard to the present day. He showed that in any given case the quantity of metal which is deposited from a solution is strictly proportional to the quantity of current and the time it flows. In fact, he provided by this electrolytic deposition of a metal the most exact method of determining the unit quantity of electric current. He showed, too, that, when we consider a number of metals, the amount deposited by a current of definite strength, as one ampere, is proportional to a set of constants known as the electrochemical equivalents, and thereby he gave an important method for checking the accuracy of atomic weight determinations in chemical work.

Probably Faraday's most important contribution to the theory of electricity following his discovery of induced currents had to do with the effect of a magnetic field upon light. In the paper presenting this to the Royal Society, he said, "I have long held the opinion, almost amounting to conviction, in common, I believe, with many other lovers of natural knowledge, that the various forms under which the forces of matter are made manifest have one common origin; in other words are so directly related and mutually dependent, that they are convertible, as it were, to one another, and possess equivalents of power in their action. . . . This strong persuasion extended to the power of light."

To understand this experiment with light, you must recall what was said in an earlier chapter regarding polarized light. Faraday had frequently tried this experiment before, but without success. Having now constructed an exceptionally strong electromagnet, he repeated it. Through a piece of heavy plate-glass lying in the field of the magnet, he passed a beam of polarized light. With a Nicol prism, which, like tourmaline, allows light to pass through it in only one plane, he examined the beam of polarized light passing between the poles of the magnet, both before the magnet had been excited and after. The prism was set so that the light passed through it when there was no magnetic field. When, however, the current had been turned on so that there was a strong magnetic field for the light beam to traverse, it was found that the Nicol prism must be turned through an angle in order to make the beam visible. That is, the plane in which it had been traveling had been twisted. Faraday for the first time had proved that light has magnetic properties, that there is some connection between light and electricity.

This discovery was to be of immense significance to Maxwell in his development of the electromagnetic theory of light. Whewell, a scientist and friend, wrote to Faraday, "I can not help believing that it is another great stride up the ladder of generalization, on which you have been climbing so high and standing so firm." Tyndall designated it "the jewel in the casket," and added, "I should liken it to the Weisshorn among mountains—high, beautiful, and alone."

One other discovery of Faraday in the field of electromagnetism must be mentioned. He had long suspected that iron is not the only magnetic substance. Nickel had been shown to have slight magnetic properties, and in 1845 Faraday added cobalt to the list. In that same year, too, he suspended by a silk cord a bar of heavy glass between the poles of his new electromagnet. He knew that a bar of iron would set itself parallel with the lines of force in the field. To his surprise, the glass swung around into a position at right angles to the field of force. That is, instead of being attracted it was repelled. He soon discovered that many other substances, including sulfur, india rubber, asbestos and tissue of the human body behaved in a similar way. Faraday said, "If a man could be in the magnetic field, like Mohammed's coffin, he would turn until across the magnetic line."

Others had made similar observations before, but they were unknown to Faraday. He divided magnetic substances into two groups—paramagnetic and diamagnetic. To the former belong iron, nickel, cobalt, chromium, manganese, platinum, oxygen—substances which are attracted by the magnet; while in the latter group are placed, in addition to those mentioned above, bismuth, antimony, zinc, lead and others—substances which are repelled in a magnetic field.

Several times in his career, Faraday broke down under the strain of his duties, but each time he recovered and returned to his work. Honors were showered upon him, both at home and abroad. The Royal Society wished to elect him to its presidency, the greatest scientific honor in England, but he refused, saying to his old friend, Tyndall, "I must remain plain Michael Faraday to the last." Twice the Society conferred upon him the Copley Medal. In his latter years, his mental powers declined, and in 1867 he died, eminently worthy of the epitaph bestowed upon him by Tyndall, "Just and Faithful Knight of God."

"THE FARADAY OF AMERICA"

In no mere complimentary sense was Joseph Henry, the first original experimenter in electricity in this country after Franklin, called "The Faraday of America." Here in the New World, far from the European centers of scientific research, independently of Faraday and as it now seems almost certainly prior to him, he discovered the fact of electromagnetic induction. However, he did not publish his discovery until after Faraday had reported his, and, therefore, he lost the technical credit of priority in the historical record.

Born in 1799, at Albany, New York, of Scotch parentage, Henry became successively professor of mathematics at the Albany Academy, professor of natural philosophy at Princeton College and first secretary of the Smithsonian Institution. It was in the Albany Academy in the half-dozen years following 1827 that Henry carried out his fundamental researches in this field. His initial interest in electricity was aroused by reports of discoveries contained in the scientific journals coming to him from abroad. Before his classes in the Academy, he repeated all the old experiments and devised new ones of his own. In particular, he experimented with the newly invented electromagnet, introducing the first improvements in its construction. In place of bare copper wire, he substituted wire insulated with silk, thus giving to other workers an innovation which soon became standard practise.

The electromagnet was as much of a mystery in those days as the X-ray was three-quarters of a century later. In popular lectures, Henry gave public demonstrations, astonishing his audiences with the great lifting power of his magnets. With one such magnet of variable strength and a battery containing only a half-pint of dilute acid and a fifth of a square foot of zinc surface, he was able to lift weights ranging from sixty to six hundred and fifty pounds. With a tiny cell having plates only one square inch in area, he made this magnet lift eighty-five pounds. An electromagnet built later for his laboratory at Princeton exerted a lifting strength of more than a ton and a half. In accordance with the molecular theory of magnetism, it seems altogether likely that the battery current merely serves to tap the magnetic forces of the molecules lying within the soft iron core. Of course, the coil of wire itself has, as we know, a magnetic field, but the greatly increased intensity resulting from the use of the iron must be due to this cause.

Henry distinguished between the "quantity" magnet and the "intensity" magnet. In the former, he wound the wire upon the soft iron core in a number of separate sections, making possible many combinations with varying degrees of strength. In the "intensity" magnet, he used many turns of a single fine wire. This magnet could be actuated by very feeble currents. It was knowledge of it, imparted by Henry to Morse, which made possible the invention of the "relay" and the success of the telegraph. In fact, in advance of this application, Henry had established in the Albany Academy a signaling system, in which he rang a bell by sending a current through a mile of copper wire. Henry, like Faraday, had no interest in commercializing his discoveries. He was the pure researcher.

In August of 1830, as it now seems, Henry succeeded in obtaining an induced current. Across the poles of a "quantity" magnet, horseshoe-shaped, he placed a soft iron bar, called an armature. Around the middle of this bar, he wound a coil of small copper wire and carried the ends to a galvanometer. When the battery circuit was closed, Henry observed a throw of the galvanometer needle, indicating a current. On breaking the circuit, he noted a deflection in the opposite direction. In June of the following year, he resumed this work, and prepared a paper describing it, which was published in the *American Journal of Science*, in July, 1832. Faraday had published his results in the previous year.

Between these two great men a warm friendship grew.

In 1837, Henry visited England, becoming acquainted with the leading British physicists and spending many hours with Faraday. On one occasion, Henry succeeded with a certain experiment in which his British colleagues had failed, whereupon Faraday, enthusiastic as a boy, jumped up, shouting, "Hurrah for the Yankee experiment." It was the work of Faraday and Henry which led to the dynamo and all the varied phenomena of induced currents which have brought the Electrical Age.

In 1842, five years prior to the same discovery by Helmholtz, Henry announced that the discharge of a Leyden jar is oscillatory. That is, it does not consist of a single stroke, so to speak, but of a series of oscillations to and fro.

From 1846 until his death in 1878, Henry was secretary of the Smithsonian Institution, performing a service to science of vast importance.

THE ELECTROMAGNETIC THEORY OF LIGHT

The electromagnetic theory of light is given precedence by many over the principle of the Conservation of Energy as being the most important contribution of the nineteenth century to the realm of physics. Certainly, this new conception produced a fundamental unification of the utmost significance in physical fact and theory. Prior to its coming, physics was regarded as embracing three main divisions—mechanics, optics and electrodynamics. The discovery of the electromagnetic nature of light united the two latter, leaving but two dissimilar groups of phenomena. And that is a chief object of physics research—to discover a fundamental harmony, a controlling rhythm, a basic unity running throughout all the diverse manifestations of Nature.

This strategic advance is inseparably linked with the name of James Clerk Maxwell, a man who added to a genius for imagination equal to that of Faraday a thorough mastery of mathematics—the beautifully expressive language of physics. Unlike Faraday, Maxwell enjoyed every advantage of education, being a graduate of two universities, Edinburgh and Cambridge. In 1846, at the age of fifteen, he was publishing papers and attending the meetings of the Royal Society of Edinburgh. J. D. Forbes, his professor of physics, gave him free range of the laboratories for original work, and he mastered almost everything of a scientific nature which he could find in the library. At twenty-five, he became professor of physics at Marischal College, Aberdeen, and later occupied the same chair at King's College, London, and at Cambridge.

Maxwell, it was who first appreciated Faraday's conception of lines of force and gave to them what the master of the Royal Institution could not give, a mathematical interpretation. It is said that he read Faraday's description of his experiments in electromagnetic induction with "something like deep, religious reverence." For the ninth edition of the *Encyclopaedia Britannica,* he prepared an article on Faraday's work, which has been regarded ever since as the most perfect tribute and just appreciation of the great Britisher in print.

Now, out of this mathematical investigation of Faraday's discoveries grew Maxwell's conviction, and indeed theoretical proof, that electromagnetic disturbances occur in the form of waves in space, or in a surrounding medium. No more than Faraday, did Maxwell like the idea of "action at a distance." In his first paper on this subject, in discussing the field of force exhibited by sprinkling iron filings on a paper placed over a bar magnet, he says: "The beautiful illustration of the presence of magnetic force afforded by this experiment naturally tends to make us think of the lines of force as something real, and as indicating something more than the mere resultant of two forces whose seat of action is at a distance. . . . We can not help thinking that in every place where we find these lines of force, some physical state or action must exist in sufficient energy to produce the actual phenomena."

As is well known, every electrically charged body is surrounded by an electric field, a field quite distinct from the magnetic field. Now building upon the work of Faraday and carrying it further, Maxwell assumed that electric currents can exist in insulators and in empty space. This was necessary, for if electromagnetic phenomena were to be generalized into a new and all-embracing conception, such currents, which he called displacement currents, must exist. To these displacement currents, Maxwell ascribed all the properties of ordinary electric currents which flow in closed conducting circuits.

Thus, they should be accompanied by a magnetic field; they should possess the ability to induce other currents and to be induced themselves in the usual way; and they, too, should possess an electric field.

Armed with this hypothesis, Maxwell was able to deduce by rigid mathematical processes the theoretical possibility of electromagnetic waves. He saw that if the field strength varies periodically in magnitude and direction, an electric wave must result. Applying the same reasoning to the magnetic field, he also arrived at the possibility of magnetic waves. He showed, too, that every electric wave must be accompanied by a magnetic wave, and vice versa. One is an impossibility without the other. Furthermore, the electric field strength is perpendicular to the magnetic field, and both are perpendicular to the common direction in which they are traveling, that is, to the direction of the current. It was at once seen that these waves were transverse, as distinguished from the longitudinal form found in sound waves.

It also turned out that the velocity of these theoretical waves in empty space is identical with that of light. That was a most significant deduction, and it led to a revolutionizing conception, for it suggested to Maxwell that light might be a form of electromagnetic energy. Here was a beautiful piece of work, entirely theoretical, and yet, if true, establishing a fundamental harmony among widely divergent phenomena. It was in Maxwell's monumental, and now classic, treatise of *Electricity and Magnetism,* published in 1873, that he set forth his theory in full.

Now let us review briefly the theoretical status of light as it stood at that time. Huyghens' undulatory theory of light in an all-pervading ether of space had vanquished Newton's corpuscular conception. For the explanation of the polarization of light, it was seen that these waves, regarded as purely mechanical waves, must be transverse. However, gases and liquids, except in the case of waves on the *surface* of liquids, where gravitation and surface tension combine to produce a peculiar condition, can transmit only longitudinal waves. To transmit waves of any sort, a medium must possess the property of elasticity, but only the elasticity characteristic of a solid, the elasticity of shape, makes possible the propagation of transverse waves. This led Fresnel to assert that the ether behaves as an elastic solid. But how could all space be filled with a solid medium and yet offer no opposition to the movements of the heavenly bodies? Here was a first-class dilemma, from which there seemed no escape. It appeared to be incredible that light and heat energy should be transmitted everywhere in space without something in which to travel, and yet the necessities of the wave form required imposed conditions totally at variance with experience, and indeed contradictory to every sense impression.

Then came Maxwell. If his theory of electromagnetic vibrations were correct and should be verified by experiment, the conception of purely mechanical waves in an elastic solid ether would no longer be necessary. Maxwell, working from the principles of mechanics, did not abandon the ether, for he needed it to transmit his waves. But his theory called for the transmission of electromagnetic energy and not mechanical energy, and for "an oscillating electric and magnetic field of force in place of periodic vibrations of the ether." Furthermore, the mathematical requirements of this field of force made necessary a transverse wave movement identical with that of light.

However, we must not assume that the ether problem had been solved. Far from it. As we shall see, no experiment has thus far been able to detect its presence. Many doubt its existence. Einstein does not need it. And yet a wave movement as necessitated by the phenomena of light and electricity presupposes something that moves. Possibly, it is only space that vibrates. But what is space? No one knows.

Unfortunately, Maxwell died in 1879, at the early age of forty-eight, nine years before the next chapter was written in this epoch of progress, a chapter brilliantly vindicating his predictions, deduced from purely theoretical considerations. To that vindication, we shall now turn.

ELECTROMAGNETIC WAVES IN FACT

In the history of physics, three outstanding verifications stand to the credit of theoretical prophecies. The discovery of Neptune, we have considered; the vindication of Einstein's predictions is fresh in the minds of all of us; that of Maxwell, of much greater practical importance, occurred between the two. The man who placed an experimental foundation under the theoretical edifice fashioned by Maxwell was Heinrich Rudolf Hertz, brilliant pupil of Helmholtz, afterward professor of physics at the Technical High School at Karlsruhe. When he had become famous he succeeded Clausius at Bonn. Despite the vast significance of this conception, it was not altogether easy to understand. Of it, Hertz himself said: "Many a man has thrown himself with zeal into the study of Maxwell's work, and, even when he has not stumbled upon unwonted mathematical difficulties, has nevertheless been compelled to abandon the hope of forming for himself an altogether consistent conception of Maxwell's ideas. I have fared no better myself."

And yet Helmholtz suggested to Hertz the fascinating undertaking of demonstrating experimentally the truth of the Maxwellian hypothesis, if it were possible to do so. The problem was to discover whether electromagnetic waves having the properties required by this hypothesis could be produced in the laboratory. If this could be done, the vast territory of light and radiant energy could be annexed to the domain of electricity, and a unification in physics of the utmost significance would be accomplished. Up to that time no other scientific quest of the century, unless it be Faraday's search for the key to electromagnetic induction, can be compared with this in interest and importance.

It was in 1886 that Hertz made some observations which led to the great discovery, and two years later he announced his results. It will be recalled that Henry and Helmholtz had in the 'forties of this fruitful century discovered that the discharge of a Leyden jar is oscillatory. Felix Savary, however, had already preceded them in this, and a decade later Lord Kelvin, unaware of this work, concluded from mathematical deductions alone that this discharge must be of an oscillatory nature. Likewise, such would be the character of the discharge of a static machine or of an induction coil. Now it was just such an electrical disturbance, if any, which should give the electromagnetic waves of the Maxwell theory.

One day in this year 1886, Hertz was experimenting in his laboratory with two short flat coils of insulated wire. Each coil was broken, leaving a short air gap between the ends. Across the gap in one of these coils, he discharged a Leyden jar and discovered that at the same time a tiny spark jumped across the gap in the second coil, although it was at a distance from the first one. Clearly, a current had been induced in the second coil. Something was traveling across the intervening space and setting up electric currents in another conductor, just as Maxwell had predicted. Could it be possible that here were the long-sought electromagnetic waves? It, indeed, looked that way.

Hertz improved his sending apparatus, substituting an induction coil for the Leyden jar and connecting to each of the spark gap terminals of the secondary a vertical copper rod, terminating in a brass plate or sheet of zinc about fifteen inches square. Here was the world's first aerial. As before, he used for the receiver a copper ring with an air gap. When he closed the primary circuit of his induction coil, sparks passed between the terminals of the secondary. Just previously to this discharge, the aerial plates became highly charged, producing, as is thought, a strain in the surrounding space, or ether, if there is such. With the passing of the spark, some sort of a disturbance traveled across to the receiver, inducing a current in it and a spark at the gap. Here was the first one hundred per cent. wireless telegraph. Hertz found that he could tune the receiver so as to strengthen or weaken the spark produced across its terminals by varying the space between them.

The next step was to investigate the disturbance taking place in the surrounding space. By means of parabolic mirrors, Hertz found that waves had really been produced and that they could be reflected precisely as light and radiant heat waves are. He then proceeded to show that these waves can also be refracted and polarized. He succeeded, too, in measuring their velocity, which turned out to be identical with that of light. Furthermore, they exhibited the phenomenon of interference. In fact, they possessed all the properties of light waves. Their only difference was in length. They were immensely longer than any waves of radiant energy known. Hertz found the waves in these initial experiments to be about one hundred feet long. The waves of visible light range in length from four to eight ten-thousandths of a millimeter, and there are twenty-five and four-tenths millimeters to an inch.

Maxwell's dream had been realized, a thing which he feared would never come. Electromagnetic waves did exist, and just as the great physicist had predicted, they were identical with light waves except in length. The waves of Hertz were beyond question electromagnetic in character. Therefore, it seemed to be established that light waves and radiant heat waves, too, are electromagnetic. That is, in accordance with the Maxwellian theory, these waves consisted of two parts—an electric wave and a magnetic wave, each perpendicular to the other and both at right angles to their direction, thus making them transverse. The concept of mechanical ether waves automatically disappeared.

This triumph of Hertz threw a flood of light on a multitude of problems and opened up new paths for research. Laboratories everywhere were soon repeating the experiments. Hertzian waves became the sensation of the scientific world. And as we know, an Italian boy shortly after began those practical investigations which in the next three decades were to girdle the earth with the voices of music and speech, enabling people everywhere "to listen in on the universe." Let it be emphasized, however, that the pure research of Hertz had to precede the applied research of Marconi. This has always been so. How should we have had the dynamo, the transformer and the long-distance transmission line without Faraday's fundamental discovery of induced currents? Davy's pioneer work in electrochemistry, followed by the discoveries of Faraday and Arrhenius, made possible the vast electrochemical industry which to-day circles the brow of Niagara. Examples might be multiplied. It is worth noting, too, that back of Hertz stood Maxwell, for Hertz was in a sense an applied researcher. His discovery, although not having a definite, practical objective, flowed from the irresistible logic of Maxwell's theory.

Again, it seemed incredible that the transmission of electromagnetic waves could occur without a medium in which they might travel. The ether seemed more necessary than ever. How could a current be induced in Hertz's resonator, as he called his receiver, without something to bridge the intervening gap? Still, the precise nature of this medium, further than that it must be such as would transmit electromagnetic waves, was almost as much a mystery as ever. But, medium of some sort, it seemed there must be, for how can we have waves without something to wave?

IN THE WAKE OF MAXWELL AND HERTZ

Before proceeding with the scientific aftermath of these discoveries, let us record that Hertz died at the early age of thirty-seven, eleven years younger than Maxwell, and before the great radio triumphs resulting from his research had come. At thirty-two, he had been elected professor of physics at Bonn, a distinction usually achieved at a much later period in life. In 1892, he developed a chronic blood-poisoning, which two years later brought the end. Still, in his brief hour of active work, Hertz achieved a place in the forefront of nineteenth-century physicists. Probably the expression "Hertzian waves" will become as much a part of our scientific vocabulary as "voltaic current" or "relativity."

A vast range of radiant energy now came under the régime of electromagnetic waves. First let us note that the visible color scale represents an octave of these waves. Color is entirely analogous to pitch in sound. It depends upon the rate of vibration and the wave length. A tuning-fork making 512 vibrations per second gives waves in the air, which are a little more than two feet long. A fork of 256 vibrations gives waves twice as long and produces a note with a pitch only half as high. Between these two notes lies an octave. So, too, with color. Between the red and the violet lies an octave of electromagnetic waves. Red has the longer wave length and lower pitch. It is this physical fact of a difference in wave length which causes the unequal refraction, or bending, in passing through a triangular glass prism and therefore results in the dispersion of light into its component colors.

Now, on either side of this visible octave of color, lie many other octaves of electromagnetic waves, recognized in various ways. We recall that Herschel in 1800 had discovered the infra-red rays, preceding the visible red, longer in wave length and manifesting themselves by their heating effects. This field is explored with a delicate instrument, known as the bolometer, which makes possible the detection of heat from a candle more than three hundred feet distant. The region of the infra-red has been extended to eight octaves preceding the visible spectrum.

Preceding the infra-red lie the Hertzian waves, ranging in length from several miles, or kilometers, to only a few millimeters. The band separating these two electromagnetic regions has now been reduced to only three octaves. The only physical difference in these sets of waves is that of wave length. In some way, this fact gives rise to different effects.

Just about the time that Herschell made his discovery, Ritter, a German, and Wollaston, an Englishman, found that beyond the visible violet, at the other end of the spectrum in what is called the ultra-violet, are rays which produce chemical effects. They blacken a photographic plate and are the rays so much used now for their physiological effects, being one of the important means of treating rickets. The waves in this region are still shorter than those in the visible violet and continuous with them. The spectrum in this direction has now been extended to eight octaves.

Now, to encroach briefly upon one portion of the next chapter, let us state here that when Röntgen in 1895 discovered the X-rays, physicists were long puzzled to know whether they were similar to light waves or not. In a textbook written in 1906, of which Millikan was a joint author, it is stated that these rays can not "be reflected, refracted, or polarized. . . . Their real nature is still unknown, but they are at present regarded as irregular pulses in the ether. . . ." However, in 1912, a Swiss physicist, Laue, in one of the most brilliant demonstrations of recent times showed that X-rays can be made to exhibit the phenomenon of diffraction, just as light rays do. Therefore, there could no longer be doubt that these, too, are electromagnetic.

Beyond the X-rays lie the gamma rays of radioactivity and the cosmic rays, of which we have heard so much in recent years and which are to be discussed in a later chapter. These are also electromagnetic.

Just one other point remains to be mentioned here. According to Maxwell's theory, light should exert a pressure. However, this effect is so exceedingly small that it long escaped detection. The total calculated pressure of the sun's rays upon the surface of the earth is only one hundred and twenty-five tons. Cavendish, more than a century ago, thought he had demonstrated this fact of light pressure, but because he did not carry out his experiment in a vacuum, it is now known that his observed effect was due to heat currents in the air. In 1901, Peter N. Lebedev, a Russian, and also the American physicists, Ernest F. Nichols and G. F. Hull, with the aid of very light mirrors made the demonstration.

It is believed that this pressure of light is responsible for the well-observed fact that a comet's tail streams away from the sun upon approach to that body. In this instance, the pressure of light on the exceedingly tenuous particles of a comet's tail is greater than the gravitational influence. Of much more significance is the evidence which this pressure affords of the possession of mass, or inertia, by electromagnetic waves. As we shall see, this property has an important bearing upon one of the major points of the Einstein theory.

We have now carried the story of electricity from its early beginning to the threshold of the twentieth century. In the following chapter, we shall find that electricity is the fundamental concept in interpreting the constitution of matter. Little did those pioneers who played with frictional electricity dream that they were toying with the most significant manifestation of Nature.

CHAPTER VI

THE NATURE OF THINGS

A BIGGER PROBLEM — ROWLAND — RELATIONSHIP BETWEEN A MOVING CHARGE OF ELECTRICITY AND AN ELECTRIC CURRENT—EVIDENCE OF ELECTRICAL NATURE OF MATTER—ARRHENIUS AND THE ELECTROLYTIC THEORY—ELECTRIC DISCHARGES IN VACUUM—SIR WILLIAM CROOKES — CROOKES TUBE — CATHODE RAYS—THEIR NATURE—RÖNTGEN AND X-RAYS—SIR J. J. THOMSON—THE ELECTRON—VELOCITY AND MASS—RADIOACTIVITY—DISCOVERIES OF BECQUEREL—QUEST OF THE CURIES—BATTLE FOR THE LAW OF THE CONSERVATION OF ENERGY—RADIUM RAYS—THE NATURE OF EACH—FIRST MODEL OF THE ATOM—EXPERIMENTAL INVESTIGATION OF THE ATOMIC NUCLEUS—PHOTOGRAPHING TRACK OF ALPHA PARTICLES—RUTHERFORD'S MODEL OF THE ATOM—ACCOUNTING FOR THE EMISSION OF ELECTROMAGNETIC WAVES—ATOMIC DISINTEGRATION—THE CASE OF URANIUM—ISOTOPES—BROTHERS OF THE ELECTRONS—REAL ALCHEMY—NATURE OF X-RAYS—DISCOVERY OF LAUE—MOSELEY AND ATOMIC NUMBERS—ENERGY OF THE ATOM—ANNIHILATION OF MATTER—ELECTRON THEORY OF MAGNETISM—MEASURING THE CHARGE ON AN ELECTRON.

THE progress of science never ceases. No imaginary state of delightful equilibrium is ever reached. Old problems vanish, but new ones inevitably appear. One advance leads to another. The objective is always in the future. Ultimate truth is elusive. We seem never able to grasp it. A veil of mystery hides the secrets of the universe. Here and there, we pull it aside, catching glimpses of apparent reality. Still, the great beyond seems almost as vast as ever.

And so it was following the establishment of Maxwell's electromagnetic theory of light—by light meaning the whole range of such vibrations. Not even a breathing spell was permitted. A bigger and more fascinating problem still had thrust itself into the foreground. When men knew, as they then did, that matter emits electromagnetic waves, they began to wonder if the nature of matter might not be electrical. Scientific curiosity had been aroused, and scientific curiosity is the most potent factor in human progress. Already a mass of isolated discoveries, bearing upon this theory, awaited interpretation. The investigators at the close of the nineteenth century, without knowing it, stood at the beginning of a veritable flood-tide of new knowledge, which was to carry them quickly into fresh areas of exploration. Let us now follow along these paths of discovery and trace the progress which, step by step, robbed matter of its one-time prestige and reduced it to a state of vassalage to electric energy.

Stop and think. Knowing beyond the shadow of a doubt that light consists of a combination of electric and magnetic waves, is it not reasonable to assume that a piece of white-hot iron, for instance, which emits all the colors of the spectrum, must have deep down in its innermost recesses some sort of an electrical structure? How else can it send forth a continuous succession of waves of an electrical and magnetic character? But what was the precise nature of this structure? What was the mechanism at the source of this radiation? If matter, as it seemed, was electrical, in what way was it electrical? Long before this, Rowland, first professor of physics at Johns Hopkins, had said that an atom of mercury must be at least as complex as a grand piano. He based this conclusion upon the complicated spectrum of bright lines which mercury emits in the state of incandescent vapor. Nothing short of some marvelous state of scientifically related parts could produce such a phenomenon. Matter in its ultimate analysis could not be altogether simple. That is, so it seemed to this keen thinker.

Let us digress a moment to say that Henry A. Rowland was born at Honesdale, in the anthracite fields of Pennsylvania, in 1848. He loved science with an intensity as great as that with which he disliked Latin and Greek. Therefore, he went to the Rensselaer Polytechnic Institute to study civil engineering. A year following his graduation in 1870, he returned to become instructor in physics. With an innate aptitude for original investigation, he conducted a research on the magnetic properties of iron, writing a paper, which, as he confided to his sister, he hoped would bring him a "good substantial reputation." However, he was too early. His ideas were not understood. It was just at this time that Maxwell's great treatise on *Electricity and Magnetism* appeared, and Rowland made bold to send his paper to the eminent Britisher, believing that he would appreciate its merit. And, indeed, he did. His enthusiasm was so great that he immediately secured the publication of the paper in the *Philosophical Magazine.* Almost overnight, Rowland had risen to distinction abroad. In another and wholly unforeseen way, too, this foreign recognition bore fruit. A little later, when President D. C. Gilman was establishing the Johns Hopkins University, he applied to Maxwell to suggest some one for the chair of physics. Maxwell unhesitatingly named Rowland. While at West Point as a member of the visiting board, Gilman summoned Rowland by telegraph. It is said that on the banks of the Hudson the two walked and talked, one telling of his dreams for higher education and the other of his dreams for science. Rowland received the appointment, being permitted a year first in which to study abroad. There he spent several months working in the laboratory of Helmholtz, performing an experiment during this period which has grown in importance with the years. Although not fully appreciated at the time, it is now regarded as a pioneer development of the first magnitude in establishing the electron theory of matter.

We have already referred to this discovery in another place, but let us state again that Rowland for the first time showed the fundamental relationship between a moving charge of electricity and the production of an electric current. On a disk, he rapidly rotated an isolated electrostatic charge and obtained a magnetic field having all the properties of the field which surrounds a current-bearing conductor. Thus, it deflected a magnetic needle in precisely the same way. Here was the first model of an electron, twenty years in advance of the discovery of this fundamental entity of all creation as an actual reality. It gave a hint, too, that an electric current might be nothing more than a swiftly moving procession of similarly charged particles of infinitesimal dimensions along a conductor. Indeed, this intriguing supposition was inescapable, but there was at that time no further experimental evidence to support it.

In advance of Hertz's crucial discoveries, this demonstration by Rowland did throw light upon Maxwell's electromagnetic theory. As had been known from the earliest experiments in this realm, an electrostatic charge at rest is surrounded with an electric field. Now Rowland had shown that such a charge in motion produces in addition a magnetic field. This magnetic field represents energy. But from whence does it come? Evidently from the work necessary to produce the motion. As long as the motion is kept up, the magnetic field continues. When that disappears, so does the magnetic field. Might it not be that a battery or dynamo is simply a means of driving along a conductor a continuous stream of electric charges? But be that as the future should determine, here were Maxwell's electric and magnetic fields. If in some way charged particles might be discovered moving in time and space with a periodic motion, electromagnetic waves would result. How this came about, we shall see.

Rowland was an inspiring guide, but he threw his students largely upon their own resources. Once when asked what he planned to do with graduate students, he replied, "Do with them? I shall neglect them." Although dying at the comparatively early age of fifty-three, he was more fortunate than Maxwell and Hertz. He lived to see the initial discoveries which ushered in the new era.

OTHER DISCOVERIES

Much other evidence pointed to some sort of an electrical structure of matter. We recall that Davy had discovered a half-dozen metallic elements by means of electrochemical decomposition. Faraday had discovered the simple laws of electrolytic action, finding that the elements had a way of being deposited from solution in proportion to a set of perfectly definite constants, known as the electrochemical equivalents. Associated with these units seemed to be a certain minimum electric charge, or atom of electricity. One thing was sure: matter at least had strong electrical affinities.

Still, why should some substances in solution conduct the electric current and thereby undergo chemical decomposition, and others not? If matter is electrical, why these differences of behavior? Why should Nature seem to play favorites? Although Grotthuss, Davy, Berzelius, Clausius and others had attempted explanations, little light was shed upon the problem until the coming of the Swedish chemist, Svante Arrhenius, in the 'eighties. In the laboratory of the great Dutch chemist, van't Hoff, at about the same time that Hertz was experimenting with electromagnetic waves, Arrhenius was developing a theory of electrolytic dissociation, equally revolutionary in its field. In his work, however, experimental fact and theory went hand in hand. His theory was simplicity itself. It readily interpreted a multitude of observations already assembled and quickly piled up a wealth of others in its favor.

Now Arrhenius assumed that an electrolyte, a compound which conducts the electric current, undergoes in solution dissociation into small positively and negatively charged particles, called ions. A non-electrolyte, such as sugar, does not thus dissociate. Why this difference, no one knows.

Furthermore, this dissociation occurs in the act of solution. For instance, if we dissolve sodium chloride, ordinary table salt, in water, it immediately dissociates into these electrically charged particles. Dissociation is independent of the passage of the current. The separation into ions has taken place before the current is passed. All the current does is to cause the positive ions in the solution to move to the negative pole, or electrode, of the apparatus, where they give up their charges and pass out of solution, and at the same time to marshal the negative ions to the positive electrode. This process we call electrolysis. A compound, which in the simple act of solution thus dissociates into ions, will conduct the current. If not, no current will flow. In passing, we may observe that when we eat salt, it is these electric units which give the taste.

Let us now see what bearing this has on the electrical nature of matter. If multitudes of compounds in solution, that is, dissolved in water, are known to consist of positively and negatively charged particles, whence the source of the charges? There seemed no answer, other than that they already existed in the structure of the matter itself and that the process of solution simply disclosed them. Non-electrolytes may also be electrical, but solution does not thus separate them into ions.

This simple theory explained a host of chemical facts and has long since been generally accepted by chemists. It also points with inescapable logic to an electrical nature of the atom. It constitutes one link in the chain of evidence.

Then, too, there were certain facts regarding gases pointing in the same direction. In its normal state a gas is scarcely a conductor of electricity at all. However, in the presence of a red-hot body a gas becomes a fairly good conductor. Later, it was discovered that the passage of X-rays through a gas produces a similar effect. What more natural than to suppose that the molecules of these gases are thus ionized, just as compounds are in solution? And it also seemed reasonable to assume that, although the molecules were originally neutral, their essentially electrical character was revealed in the process of ionization. That is, in the dissociation one ion became positively and the other negatively, not from the outside influence, but from the electrical structure of the molecule itself.

And so, bit by bit, the evidence accumulated.

NEW PATHS TO TREAD

Side by side with the discovery of electromagnetic waves and Arrhenius' laws of electrolytic dissociation, another line of research had been opening up a mystic maze of new paths to tread. Back in 1853, A. Masson, of Paris, had sent the discharge from a powerful induction coil through the Torricellian vacuum above the mercury in a barometer tube. The result was a beautiful display of colored light. Others began to exhaust tubes, passing through them either the discharge from an induction coil or from a static machine. Heinrich Geissler, a glass-blower of Tübingen, became so skilful in the preparation of these vacuum discharge tubes that they have ever since been known as Geissler tubes. Beautiful colors were obtained by leaving in them traces of various gases. Whoever has seen it can never forget the brilliant display of changing colors which appears in a long glass tube as the air is gradually pumped out and at the same time the discharge from an induction coil is passed through it, particularly if this is done in a darkened room.

However, thus far this work was leading to no new knowledge, either of electricity or of gases. Fascinating experiments, these discoveries were, and nothing more—only gratifying a scientist's insatiable curiosity to know what will happen under a new set of conditions. Here was pure research—simply experimenting for the sake of uncovering some fresh fact of Nature. Those men did not know that they were taking the first steps along a trail that would lead to a revolutionizing conception of the structure of matter. Like coral polyps, they were, each contributing his bit to a skeletal framework which one day would lift an island above the ocean's waves. And so they worked on, not for fame or commercial gain, but for the love of truth.

Now there comes upon the scene the most gifted pioneer in this new field, Sir William Crookes. A picturesque character among British scientists, his career is the more remarkable from the fact that he received little regular schooling in his boyhood, and never went to university or held a professorship. Born in 1832, the son of a London tailor, the chief delight of his youthful years was a laboratory, in which he performed all sorts of experiments. He read, too, everything upon science that he could discover. He was a forerunner of some of the most important researchers in the closing years of the last century, and an early investigator of radioactivity. He, too, was interested in spiritual phenomena. He lived until 1919, thereby witnessing as well as participating in the revolutionary discoveries of the present era. Probably his most notable achievement was the discovery of the element thallium. He also invented the radiometer for the detection of radiant energy.

In a series of beautiful experiments, beginning in 1878, Crookes reduced the electrical effects in a high vacuum to a matter of scientific precision. He produced more highly exhausted tubes than any of his predecessors and subjected the electrical discharges to experimental analysis. So completely did he identify himself with this pioneer research that this sort of a vacuum tube has ever since been designated by his name.

Let us pause to note that sealed into each end of a Crookes tube is a metal electrode. The positive terminal is called the anode, and the other, the negative, is the cathode. The mysterious rays came from the cathode, and they have ever since been known as cathode rays. Crookes proceeded to show that in a darkened room these rays manifest themselves in three ways: they produce a brilliant glow, or fluorescence, as it is called, in the walls of the glass tube; a metal target placed in their path becomes very hot; and this target casts sharp shadows on the opposite wall of the tube. These were the facts—apparently only another set of strange physical phenomena. Little did Crookes realize that he stood at the beginning of a new scientific highway leading over the divide to a wondrous realm. But his life-long bent for experimenting urged him on and soon his ingenuity had provided the key to the gate.

First of all, these rays of mystery cast the shadow of a big question-mark against the scientific background. What were they? That was the question being asked on every hand. Essentially the same problem presented itself which two centuries before had troubled Newton and Huyghens in their consideration of light. Were they simply a new type of ether waves, or did they consist of something similar to Newton's corpuscles shot forth from the cathode at high velocity? Speculation was of no avail. There was only one way to tell. Carefully planned experimental attacks must be made all along the line. Only thus could this manifestation of energy be made to yield its meaning.

"If these rays are nothing more than rapidly moving particles, their impacts should produce motion," thought Crookes. Accordingly, he built between the terminals of one of his tubes a little track, railroad-fashion, and on it he placed a tiny paddle-wheel of light metal with its axles resting freely on the rails. Then, he exhausted the tube, sealed it off and passed the discharge. That simple experiment told the story. Immediately, the wheel began to turn, moving along the track from one end to the other. No hitherto observed effect of hypothetical ether waves could produce such a result. Of infinitesimally small particles of some sort, these rays must consist. But what was their nature? Were they electrically charged, and, if so, what kind of charges did they bear?

One experiment suggests another. What more natural than to apply a magnet to these particles? That should unmask them and reveal their character. And so Crookes did. Just in front of the cathode, he placed an opaque screen with a fine slit in the middle. Then, lengthwise of the tube, he placed vertically another screen, covered with zinc sulfide, a substance which fluoresces brilliantly under the influence of cathode rays. When he excited the tube and sent these particles down the line, a bright streak of light traced itself along the zinc sulfide screen. Again, Crookes did the perfectly logical thing. He placed near to the tube the positive pole of a magnet, for, he argued, since these missives of energy spring from the cathode, the negative terminal, they should be negatively charged. And he was right. Sure enough, just as he had anticipated, they turned aside from the path they were beating in a bee-line for the anode, and curved downward toward the magnet, leaving a telltale streak on the screen as evidence indubitable. One more question had been answered. These rays consisted of negatively charged particles. Fascinating work, this was. Step by step, Crookes was unveiling secrets which had been patiently waiting for revelation from the beginning of time. Still, nothing that might be labeled "practical," had emerged from these discoveries. It did not seem likely that any industries could be founded upon them. In short, they hit no one in the region of the cash register.

A new fact now came to light. Bodies upon which these cathode particles fell received negative charges. No longer could there be any doubt as to their character. Additional experimenting, too, revealed their velocities—showing that they sometimes reached the astounding speed of one hundred thousand miles a second. Aside from the velocity of light, nothing like this had ever before been known. And, as we shall see, this velocity was to prove a bulwark of support to the forthcoming theory of relativity.

By this time, scientists in laboratories everywhere were repeating the Crookes experiments. Some were trying to induce these swarms of atomic meteors to come outside their vacuum prison house and display their charms in the open. Lenard, now professor of physics at the University of Heidelberg, first succeeded in this. Through a small window of aluminum, he obtained feeble rays. Now the famous Coolidge cathode tube, employing nearly a million volts, shoots billions of these charged bullets into the air at speeds closely approaching that of light. In the laboratories of the General Electric Company, Doctor Coolidge produces remarkable chemical and physical changes from the impacts of these missiles.

Still, much more needed to be known about these newcomers in the physical world. The pioneer work had by no means been completed. Years passed and not much that was new developed, save one highly significant fact. It was found that, no matter of what material the cathode terminal of the Crookes tube was made, the same identical particles always appeared. I venture to say that no more interesting discovery in the whole of nineteenth-century physics had been made than this. It seemed to strike at the very foundations of the structure of matter itself. Here were electrical units, all precisely the same as two peas in a pod, emerging as a common constituent of every sort of matter. Could it be possible that these were the primordial building-blocks of the universe? Had a dream of the ages come true? Was there a common denominator to which the ultimate constituents of every element might be referred? And was matter in its last analysis truly electrical? Here were questions freighted with the utmost import for the interpretation of this universe of stars and atoms, sentient beings and civilizations. But scientific discovery will not be hurried; it takes its time.

It will be recalled from the initial chapter in the book that this was the period when physicists were congratulating themselves that all the fundamental discoveries had been made. Nineteenth-century physics is regarded as having ended in 1895, the year in which the most startling discovery of this whole epoch was made. Like so many other strategic turning-points in scientific progress, it came about by accident. The man who brought it to light was Wilhelm Conrad Röntgen, and as you have already guessed, this next addition to the growing fund of knowledge was that of the X-rays. It seems surprising that no one had made this discovery before. Men had been experimenting with Crookes tubes for fifteen years. Still, no one had blundered on to the peculiar conditions necessary to reveal this remarkable effect.

Röntgen was one day working in his laboratory at the University of Wurzburg when, for reasons known only to himself and possibly not clear even to him, he threw a black covering of opaque material over a Crookes tube and set it into action. Now here is where the accident comes in. There happened to be lying upon the table close to the apparatus a paper screen covered with a chemical compound known as barium-platino-cyanide. To the amazement of Röntgen, this screen began to glow, or fluoresce, brilliantly. Something extraordinary was happening. In complete defiance of all the established rules of orthodox science, here was a new kind of radiation capable of passing straight through matter hitherto thought to be entirely opaque to light rays. It was an astounding performance.

With meteoric rapidity news of this latest scientific sensation spread throughout the world. However, the report was received not without some degree of skepticism. The current issue of the *Scientific American* contained the following interesting account:

> "There have been received from Europe by cable very insufficient accounts of a discovery attributed to Professor Routgen, of Wurzburg University. By the use of a radiant state of matter tube, a Crookes tube, it is stated that he has succeeded in obtaining photographic effects through opaque objects. It has long been known that ether waves of long period would pass through matter opaque to short waves, and that such a screen as is afforded by a plate of blackened rock salt will sift out short waves, while long waves pass through it. In some unexplained way Professor Routgen, it is claimed, has succeeded in affecting the sensitive plate with waves which had passed through an opaque body. Metals cutting off all rays alike would produce a

shadow, so that a metallic object in a box or embedded in the human system could be made to give some kind of an image. The operations are said to have been conducted without a lens, entirely by shadow.

"This is about the substance of the reports. It is yet too soon to indulge in the wild possibilities that have been suggested for the process. When the details reach us, the process will probably prove to be of scientific rather than of practical interest."

How well the "wild possibilities" of this discovery have been fulfilled, I leave you to judge. The misspelling of Röntgen's name indicates that he was not then known to fame. Seldom do we have a better example of an achievement which proves to be at once of the highest scientific interest and of supreme practical importance. The X-ray, of vast significance in itself, has afforded the magic key to new storehouses of knowledge, and has become a willing soldier in the service of the hospital, industry and the home.

It soon became apparent that wherever these cathode particles strike upon the walls of the Crookes tube, or better, upon a target placed within the tube, this new and highly penetrating form of radiant energy is produced. The precise nature of these rays, however, long remained a mystery. The method whereby they were determined to be electromagnetic waves in the ether, so exceedingly short as to require two hundred and fifty million of them to measure an inch and a rate of vibration of three quintillion per second to produce them, will be given later in the chapter. For comparison, we might observe that the octave of visible light requires frequencies of only four hundred to eight hundred billions of vibrations per second, really a stagecoach speed.

Now let us come to what is probably the most important point regarding these cathode particles. How massive are they and of just what do they consist when we delve deep down into the innermost recesses of their constitution? To answer these questions takes us back to the year 1881 and

Sir J. J. Thomson, then one year out of Cambridge, where he had distinguished himself as second wrangler and Smith's prizeman and had acquired an intensive training in mathematical physics. From 1884 to 1918, he was Cavendish professor of experimental physics at Cambridge, working in the laboratory which had been built and equipped by Maxwell. Incidentally, it is now seen that the burden of supervising the construction of this laboratory on the part of Maxwell required time which could ill be spared from the priceless work of research. Since 1918, Thomson, who has been a big factor in shaping the physics of the present era, has held the honorary Cavendish professorship.

Thomson built upon the work of Rowland. From the data provided by Rowland's historic experiment and experiments of his own, he concluded that a moving electric charge possesses mass, or inertia, the common property of all matter. As we have seen, such a moving charge creates a magnetic field. This field represents energy and is the product of the work done upon the charge to give it motion. The mass seems to be due to the energy of the magnetic and electric fields. Here was the first suggestion of the far-reaching concept of modern physics that mass and energy are equivalent. Thomson named this inertia of a moving electric charge electromagnetic mass. The highly interesting question at once arose as to whether the mass of all matter might not be due to this same electromagnetic inertia. A little later, Thomson was to be the chief figure in another determination which was to throw a flood of light upon this new aspect of physics and also to give the clue to the nature of the cathode particles.

In 1897, this most resourceful physicist sought to know how heavy one of these particles is, in other words, its mass. Impossible to measure such an absurdly small unit! Yes, to the uninitiated, but Thomson did it. By extraordinarily precise and perfectly reliable methods, he determined that a cathode particle is about one eighteen-hundredth as heavy as the hydrogen atom, up to that time regarded as the lightest unit in creation and the smallest. The most accurate of more recent measurements places this fraction at one eighteen-hundred and forty-fifth. No longer could the atom be thought of as a simple unit. It must be exceedingly complex, and these newly discovered units were a common constituent of every kind of atom.

Thomson had not finished his quest. How much of the mass of a cathode particle could be attributed to the negative charge of electricity and how much to some hard core of old-fashioned matter, which presumably served as a carrier for the charge? It was not difficult to measure both the quantity of the charge and the velocity with which it moved. The result was the astounding discovery that the entire mass was electromagnetic. That is, a cathode particle, now named the electron, was nothing but a tiny bit of pure negative electricity. Certainly, there could no longer be any question that matter was in large part electrical in its structure. And could it not also be that, inasmuch as a moving charge of electricity behaves precisely as an electric current, a battery or a dynamo delivers nothing to a conducting circuit but a stream of swiftly moving electrons? To this conclusion, the scientific world has long since come.

This was a revolutionizing conception, both for chemistry and for physics. Old moorings were loosed. Matter and energy were equivalent. Energy, too, possessed inertia, or mass. Mass became a property of motion, or velocity. The faster a body moved the greater its energy, and also its mass. When a body cools, its molecules vibrate less rapidly. It therefore loses energy and at the same time its equivalent, mass, becomes less. It at once became apparent that, if we can in any way impart energy, potential or kinetic, to a body, its mass, that is, its inertia, is automatically increased. Such ideas made old-time scientists rub their eyes and wonder if they were still living in the same world. Incidentally, they paved the way, in one important respect, for the coming of the theory of relativity. As already indicated, this discovery, too, started scientists to wondering if a considerable part of the mass of the atom might not be due to the movements of electrons within it—in other words, electromagnetic. In a way, the substantiality of the universe seemed to vanish.

Experimenting with Thomson in the Cavendish laboratory at the time he made these investigations was a pupil, Sir Ernest Rutherford, since become one of the most distinguished researchers in the field of radioactivity. Of this remarkable period at the very beginning of the new era, he has given the following account:

> "The proof in 1897 of the independent existence of the electron as a mobile electrified unit, of mass minute compared with that of the lightest atom, was of extraordinary importance. It was soon seen that the electron must be a constituent of all the atoms of matter, and that optical spectra had their origin in their vibrations. The discovery of the electron and the proof of its liberation by a variety of methods from all the atoms of matter was of the utmost signification, for it strengthened the view that the electron was probably the common unit in the structure of atoms which the periodic variation of the chemical properties had indicated. It gave for the first time some hope of the success of an attack on that most fundamental of all problems—the detailed structure of the atom. In the early development of this subject, science owes much to the work of Sir J. J. Thomson, both for the boldness of his ideas and for his ingenuity in developing methods of estimating the number of electrons in the atom, and of probing its structure. He early took the view that the atom must be an electrical structure, held together by electrical forces, and showed in a general way lines of possible explanation of the variation of physical and chemical properties of the elements, exemplified in the periodic law."*

Confirmation of a scientific supposition is sometimes swift and certain. So it was with one aspect of this new conception of mass. In 1901, W. Kaufmann demonstrated that the mass of an electron actually increases as its velocity approaches that of light. At ninety-nine hundredths of the velocity of light, it has been shown theoretically that the

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*[*Science*, Vol. 58, p. 211.](#)

mass becomes seven times as great as when at rest. Einstein's theory of relativity makes it infinity at the full velocity of light. However, we are here to think of mass in the sense of inertia.

The full significance of this experimental fact can only be appreciated when we consider that for a century the Law of the Conservation of Matter had been regarded as impregnable. Mass was, therefore, an invariable quantity. Under no circumstances could the mass of a body be increased or decreased in the slightest degree. And as a matter of fact, for any velocities possible to obtain here on the earth, aside from those of electrons and the alpha particles shot forth from radioactive elements, mass is for all practical purposes invariable. Theoretically, mass always varies with velocity, but it is usually so slight as to be impossible of measurement.

If we stop to think of it, this discovery of Kaufmann's was only an extension of the experiment performed by Rowland just a quarter of a century before, and a confirmation of Thomson's deductions. Now that it was known that an electron is nothing but a charge of negative electricity, its motion should produce a magnetic field, just as Rowland's charge had done. Furthermore, the faster it moves the stronger should be this field and, therefore, the greater should be the energy content. But, since energy and mass are equivalent, this increase of energy should also give a larger mass. We see, too, that this mass at every stage of the process is electromagnetic. With what infinite satisfaction, Maxwell, and also Hertz and Rowland, would have contemplated these results! They were the pioneers—denied the privilege of witnessing the full fruit of their discoveries.

RADIOACTIVITY

Nevertheless, great as these victories were, they made possible no concrete picture of the internal structure of the atom. In just what way the electrons and their theoretical brothers of positive electrification might be grouped to form some sort of an electrical unit did not appear. However, the tide of discovery was still rising. Indeed, revelations overwhelming in their significance were already being made. In awe and consternation, the cock-sure standpatters of a half-dozen years before viewed the spectacle. Old frontiers vanished. New ones appeared and disappeared with kaleidoscopic rapidity. Not in a hundred years had progress been so completely on the wing.

The man who lifted the veil hiding the secrets of radioactivity and thereby gave the first glimpse of a whole new realm of natural phenomena of the most fascinating sort was Henri Becquerel, of the University of Paris. He bore a distinguished name, his father and grandfather having been worthy scientists before him. It was in 1896 that he began his investigations. That was the year in which Marconi went to England to demonstrate the marvelous practical utility of the Hertzian waves. The X-rays had scarcely ceased to cast the magic of their glamour over the scientific imagination. Thomson was about to begin his researches on the electron. Zeeman had demonstrated a remarkable effect of magnetization upon spectral lines. Much awaited explanation. It was fitting that Becquerel should choose this auspicious moment for the world's most unique discovery regarding the constitution of matter.

His curiosity aroused by the new knowledge of the X-rays, Becquerel began an investigation of the light-giving properties of phosphorescent substances in general. Again, let us emphasize that this was pure research. It promised no dividends, other than the satisfaction of having added to the sum total of human knowledge. But the scientist asks no favors of the goddess of fortune. His only purpose is the pursuit of truth.

Why Becquerel chose uranium, the element of all others best suited to serve as a key to unlock the door leading to the world of radioactivity, no one knows. Possibly it was just another of those fortunate accidents which occasionally punctuate the course of scientific progress. But choose it he did, and he began to wonder if this substance, exposed to sunlight, might not give off radiant energy capable of penetrating opaque matter as X-rays did. The only way to know was to try. He put the metal for a time under the influence of the bright rays of the sun, carried it into his dark room and placed it upon a photographic plate wrapped in heavy black paper. After a time, he removed the plate and developed it. He had put a question to Nature and was about to receive the answer. How momentous the question was, he did not then know. Presently, the answer came, clear as noonday. The plate had been darkened. Uranium did give off rays which penetrated opaque matter and produced chemical changes in silver salts. Surely, some deep mystery was in the offing. He repeated the experiment, substituting thin metal plates for the black paper. The result was the same. Each time, however, before making the test, Becquerel had exposed the uranium to the sun's rays. Then, one day the sun did not shine, a circumstance not unusual in Paris. With that curiosity which never forsakes a scientist urging him on, he wrapped a photographic plate in heavy black paper, laid the uranium upon it, and thrust the two into a drawer. There, almost forgotten, they remained for several weeks. Then Becquerel developed the plate. Again, the image appeared. Here was something more remarkable still. Uranium of itself, unaided and alone, gave off these penetrating rays. Was he standing in the presence of a form of natural X-rays? It certainly looked that way. Still, there appeared to be nothing of practical value in all this. Why carry the pursuit further? With all our sordid commercialism, probably not one person in a thousand would take that attitude. Original discovery is the most fascinating game in the world.

I do not need to tell you here the story of Madame Curie, the Polish girl, unknown to fame and fortune, who sought permission to undertake an exhaustive examination of all the elements to discover whether there might not be others also possessing radioactive properties. You know that this quest, in which this girl chemist in a foreign capital was aided by her youthful husband, Pierre Curie, culminated in the discovery of a number of radioactive substances, chief of which was the new element radium, exhibiting two and a half million times the activity of uranium itself. That this remarkable substance was an element there could be no question, for, viewed with the spectroscope, it displayed a perfectly definite bright-line spectrum, distinct from that of any other element. Quickly, its properties were discovered, and they presented a unique and fascinating array. Like uranium, this newcomer darkened photographic plates, but to an extraordinarily greater degree. In common with X-rays, its radiation would ionize the air. It was found also that radium would excite phosphorescence, liberate large quantities of heat, produce chemical changes and destroy minute organisms.

These truly revolutionary discoveries at once precipitated a battle royal over the integrity of the principle of the Conservation of Energy, the foundation-rock of nineteenth-century physics. Every hour radium generates enough energy in the form of heat to raise the temperature of an equal weight of water from the freezing-point to the boiling-point. Furthermore, early observations did not seem to indicate any diminution in this steady evolution of energy. Could it be that here was something as good as perpetual motion? The scientific world seemed to be face to face with a bold defiance of a great law of Nature. As Gustave Le Bon said, "If the principle of the conservation of energy—which by-the-by is simply a bold generalization of experiments made in very simple cases—likewise succumbs to the blows which are already attacking it, the conclusion must be arrived at that nothing in the world is eternal. This great divinity of science would also be condemned to submit to that invariable cycle which rules things—birth, growth, decline and death."

But the world could not long be left in such a bewildering state of contradictoriness. Scientists rallied to the defense of this law, bought at much cost, as valiantly as the feudal knights of yore yielded service to their king. Out of the welter of hypotheses offered in explanation emerged the one, later supported by experimental evidence, "that the atom of a radioactive substance giving off energy passes, in the manner of a molecule, from an unstable combination into a stable condition." As Rutherford and Soddy showed experimentally, radioactive substances undergo disintegration and in so doing liberate subatomic energy, which manifests itself outside the atom in various ways, such as motion, heat, light and chemical effects. But this energy is not newly created. This work also soon led to a knowledge of what is called the life-cycle of a radioactive substance. This means in the case of radium, for instance, that in seventeen hundred and thirty years, half of any given quantity of this element will have disintegrated. In another equal period half of the remainder will disintegrate, and so on. That there should be any left in the earth now pointed to one or the other of two conclusions. Either early geologic rocks had possessed large quantities of radium, or radium is continually being born somewhere in the earth's crust. To this latter belief, scientists have come. Indeed, there seems to be no question of the truth of this view.

And so the law of the Conservation of Energy survived the crisis. When the smoke of battle had lifted, Crookes said, "A few decigrams of radium have undermined the atomic theory of chemistry, revolutionized the foundations of physics, revived the ideas of alchemists, and given some chemists a bad attack of swelled head." However, he did not refer to the fundamental principle about which the storm had chiefly raged. In certain other respects, his words were, indeed, true.

Now come the interesting disclosures of this line of research, as far as the electrical nature of matter is concerned. Three of the most gifted investigators of recent times attacked this phenomenon of radioactivity with vigor.

They were Sir Ernest Rutherford, Sir William Ramsay and Professor Frederick Soddy. Although they are all Englishmen, Rutherford was born in New Zealand and from 1898 to 1907 was professor of physics at McGill University in Canada. In 1919, after having served for twelve years at the University of Manchester, he succeeded Thomson as Cavendish professor at Cambridge. Ramsay is remembered chiefly for his discovery of the rare gases of the atmosphere, and the name of Soddy will forever be identified with this new form of radiant energy.

Under the search-light of their attacks, the fact soon emerged that radium yields three distinct sets of rays—alpha, beta and gamma. The alpha rays turned out to be the most powerful missiles known to science. They are positively charged particles, four times as heavy as the hydrogen atom and moving with velocities close to twenty thousand miles a second. Thus, it is seen that they possess large quantities of kinetic energy. Being so large, their penetrating power is small, but they are exceedingly active in rendering gases conductors, that is, in ionizing them. Still, the most astonishing circumstance was yet to be revealed. Rutherford succeeded in coralling a small quantity of these particles. Then, he examined them with the spectroscope, and, lo, they gave the bright-line spectrum of helium. Here was natural alchemy. Under his very eyes, one element had broken down, yielding another. The old definition of an element, as something which can not be changed into anything different from itself by any known means, vanished into thin air. The element as such was not inviolable. However, the process is wholly a natural one. Man can neither accelerate it nor stay it. He may stand on the side-lines and watch the procession go by, but that is all. Nevertheless, this was a wonderful discovery, the importance of which was to grow. The positive charges on these particles, too, constituted one more link in the chain of evidence for the conception of some sort of an electrical structure of matter.

With the beta rays, however, came the most significant revelation of all. They proved to be identical with the cathode particles of the Crookes tube. That is, they were electrons—nothing more nor less than negative charges of electricity. And they were being shot forth from the atoms of an element. Surely, the earlier suggestion that these midgets of the universe might be a common constituent of all matter was finding confirmation. Uranium, thorium and actinium—other radioactive elements—also liberated them, and it will be recalled that, no matter of what elements the cathode of a Crookes tube might be composed, electrons were invariably shot forth. More and more, it appeared certain that the atoms of the elements are electrical. The velocities of these beta particles exceeded all previous bounds. They ranged from 60,000 to 180,000 miles a second, close to the velocity of light. And their penetrating power was astonishingly large. While a sheet of aluminum foil only 0.005 of a centimeter thick will completely stop alpha particles, it proved to be no obstacle at all to the beta radiation. These high-speed electrons passed straight through it with ease.

Then, there were the gamma rays. It soon developed that this was the radiation that had affected Becquerel's plates. It consists of a highly penetrating form of X-rays—very "hard" as we say now. It became clear enough, too, how they happen to be formed. Just as ordinary X-rays are the result of the impacts of electrons in a Crookes tube, so gamma rays are set up by the impacts of beta particles on surrounding matter. The higher velocity of beta particles over the electrons in a Crookes tube accounts for the more intense form of radiation.

Vast progress was being made, but multitudes of fresh problems were thrusting themselves to the fore. For one thing, physicists wished to know the parent source of radium. Whence did it take its origin, and how long was it aborning? This opened up the whole subject of radioactive disintegrations. However, before we can interpret these phenomena, we must get a picture of the internal structure of the atom, as it was gradually taking shape.

A PICTURE OF THE ATOM

The first speculative model of the atom in line with the new knowledge was the product of Sir J. J. Thomson. All thought of the atom as a simple and indivisible unit had now been abandoned. Although only the atoms of radioactive elements were known to be complex, no one doubted that the atoms of all elements had a common structure. Negatively charged units had been discovered. Associated with these electrons must be positive electricity, whatever might be its concrete reality. Accordingly, Thomson imagined a sphere of positive electrification, of just sufficient strength to neutralize the sum of the negative charges on the electrons distributed throughout it. The electrons were symmetrically placed and free to oscillate, thus accounting for the emission of radiant energy. This was an excellent start, but the Thomson model soon ran counter to a number of experimental facts, and a fact is the most stubborn thing in the world. In science and politics alike, it makes and unmakes empires.

Rutherford was the man who bowled the Thomson atom from its seat of power, placing one of his own creation upon the throne, which for a considerable period wore the purple and wielded the scepter of authority. Then that, too, was cast down, to be superseded by another, which has already had its day and is now being abandoned for more promising and influential candidates of the royal household of the atomic dynasty.

Again let it be emphasized that these various conceptions of atomic models, while in the very nature of things somewhat speculative in origin, all have a substantial basis of experimental fact. Thus, Rutherford began shooting high-speed alpha particles through matter in a gaseous state. Let us bear in mind that an alpha particle carries a positive charge of electricity, in fact two unit charges. To the surprise of Rutherford, calculation showed that one of these missiles penetrated many thousands of the atoms of the gas without its direction being appreciably affected. Only once in about eight thousand times did it seem to meet with a head-on collision. Then it would swerve in a curve to one side and pass off in another direction. But what should make it turn aside at all? Manifestly, a heavily charged center of positive electrification. Immediately, however, an illuminating fact thrust itself into the foreground. If there was only one chance in eight thousand for a heavy alpha particle to make a head-on collision, the atom must contain a positive nucleus of exceedingly small relative proportions. From the amount of the deflection and the curved path of the foiled particle, Rutherford was able to calculate the magnitude of the positive charge of the nucleus. This at once disclosed the fact that practically all of the mass of the atom is concentrated in this strategic center. For instance, the hydrogen nucleus turned out to be about eighteen hundred times as massive as an electron. Thus, Rutherford was able to determine for a considerable number of elements the number of positive charges on the nucleus and the mass of the nucleus. These experiments always showed that, while the mass of the atom is all in the nucleus, this unit is exceedingly small in comparison with the atom as a whole. As we shall see, another highly significant circumstance also emerged.

It is perfectly clear now why Thomson's atom was short-lived. If the atom were simply a sphere of uniform positive electrification with electrons embedded in it, alpha particles, when fired through a mass of these atoms, would not behave as they did. There would be no sharp deflections. Probably, under such conditions, a particle would move in a straight line, and as it plowed its way through, it would soon spend its energy, thus bringing its mad career to an abrupt end.

Before we describe the Rutherford model, let us give a beautiful method of photographing the track of an alpha particle and thus giving visible proof that these deflections were not fictions of the imagination. The experiment was devised by C. T. R. Wilson, a distinguished physicist, trained by Sir J. J. Thomson. It is well known that for the condensation of water vapor particles of dust are required to serve as centers about which the droplets may form. Ionized molecules of air, however, will serve just as well. Now it is known that alpha particles will ionize air, which simply means that they knock loose some of the electrons from the atoms of the molecules, thus leaving the nuclei with their positive charges not fully neutralized. The result is positive and negative ions. Taking advantage of this fact, Wilson shot alpha particles into moisture-laden, dust-free air, at one and the same time ionizing the air and producing particles of condensed water vapor. As he did so, he photographed the resulting paths. In this way beautiful examples of this whole phenomenon were obtained.

Wilson tells us that the idea of this experiment came to him as he was watching the behavior of clouds in his native hills of Scotland. On one side of the mountain, the ascending air, expanding and therefore cooling as it rose, condensed its water vapor to form clouds. On the other side, the descending air, becoming more compressed at lower levels and therefore warmer, caused the clouds to evaporate and disappear. He attempted to form artificial clouds by allowing moist air to expand. From these experiments, he discovered that centers of condensation, such as dust particles, are essential for the production of clouds. Without them, it is very difficult to make water vapor condense. This observation, plus a little thought, led to the historic experiment just described.

Rutherford now had the basis for the construction of a new atom model. To get a better view of it, suppose we magnify the sizes of all atoms and molecules ten billion times. This scale would make a bird shot as large as the earth and an average atom about three feet in diameter. As we view such an atom, we behold one of the most porous units in all creation. The ancient conception of a hard, smooth, shining sphere vanishes utterly. In its place, we behold a vast solar system with central sun and planets, which revolve about this sun at almost inconceivable velocities. Far away at the center of the sphere, we descry the solar nucleus, almost lost to view even on the prodigious scale that we have set. But between the electrons themselves and between the electrons and the nucleus are vast dreary wastes of space, relatively as large as are those in the heavens above.

Let us look again, examining in turn the atoms of many elements. True, they are all built on the same pattern, but the number of electrons in the planetary groups varies widely. Here are atoms of hydrogen, each with its nucleus and a solitary electron revolving about it. An atom of helium appears to have two planetary electrons. The planetary group known as lithium is able to boast of three electronic units. Presently, a definite sequence, a regular order, begins to emerge from this helter-skelter, hit-and-miss aggregation of atomic units, for, lo, we discover that the number of these planetary electrons increases, step by step, one at a time, from hydrogen, the simplest, to uranium, the heaviest and most complex. From hydrogen with one revolving electron to uranium with its ninety-two, we find a perfect gradation, in other words, ninety-two atomic models. True, two of these elements have not yet been discovered in Nature, but there is no doubt of their existence. Some of these electrons, too, are moving, according to Rutherford, with velocities equal to half that of light.

Experimental evidence also showed that the number of positive charges on the nucleus was in each instance equal to the number of planetary electrons. Thus, when an atom possesses its full quota of electrons and its family circle is complete, it is electrically neutral. If, however, it has been robbed of any of these constituent units, as, for instance, when atoms of a gas have been ionized by the presence of a red-hot body, by X-rays or by the passage of alpha particles, the electrical balance is disturbed, and positive and negative ions appear. Something similar to this occurs in the ionization of a compound in solution, according to the electrolytic dissociation theory of Arrhenius.

It became apparent that a definite number, known as the atomic number, could be assigned to each element. This number is now regarded as the most significant constant related to atomic structure, of more importance than the atomic weight itself. Not only does it denote the number of planetary electrons and the corresponding number of positive charges on the nucleus, but it also indicates the position of the element in the periodic grouping of the elements, one of the most fundamental of chemical laws.

Such was the Rutherford model. A wealth of experimental evidence supported this conception. The nucleus was, in comparison with the rest of the atom, exceedingly small and it was positively charged; planetary electrons were not a dream; the number of positive charges on the nucleus had been measured in a sufficient number of cases to make reasonably sure the conclusion that this number in each instance agreed with the number of revolving electrons; and there was no question that the electrons must be in motion. Otherwise, they would fall into the nucleus, just as the earth would fall into the sun, were it not in motion, thereby annihilating the atom and causing the dissolution of the universe.

Furthermore, this model could account for the electromagnetic waves of Maxwell's theory and Hertz's experiments. That was a most important consideration. Here were electrons revolving in circular orbits, for such was the form assumed by Rutherford. The electron from its very nature possesses an electric field. Being in motion, it also gives rise to a magnetic field. With this orbital motion are associated two other factors—acceleration and periodic motion. The curved path of the electron subjects it to a constant acceleration toward the nucleus, just as the moon is constantly drawn toward the earth with accelerated motion. It will be recalled that this fact was the basis of Newton's proof of the Law of Gravitation. Now when the motion of an electric charge changes in any way, a change in the electromagnetic field automatically takes place, thus giving rise to an electromagnetic wave. This accelerated motion of the electron toward the nucleus is such a change. However, if these waves are to be emitted in regular succession, the disturbing cause must be periodic in its occurrence; this periodic effect, the circular motion of the electron in its orbit provides. Imagine that you are looking edgewise at this orbit. The electron will appear to move to and fro along the diameter of the orbit, executing a periodic movement like the swinging of a pendulum. Therefore, electromagnetic waves are generated, and when the atoms are sufficiently excited, as when heated or under the influence of an electric discharge, these waves are short enough to produce the effect of visible light.

Rutherford had carried his comrades a long way forward in the interpretation of the electrical nature of matter. The jungle of atomic mysteries was beginning to yield its meaning. The outlines of the atom were taking shape on the canvas. The lights and shades were coming out. The perspective was improving. The atom was not yet quite ready to sit for its picture, but scientists were hopeful that it soon would be. As we shall see, however, the Rutherford model ran afoul of hidden shoals. It could not account for all the facts of observation. It proved to be only a provisional atom, serving well for a time, but, like the stage-coach and the pony express, giving place to something better. Let us pause to emphasize at this point that this is always the method of scientific research. The scientist is never a worshiper of the past; no creation of his ever becomes sacred. He faces the future with an open mind; his theories are always tentative. Facts are the building-stones with which he works; when assumed facts prove to be otherwise, the edifice falls. There is no attempt to cling to ideas that will not stand the test of time. And so Rutherford's atom was doomed to pass into obsolescence, as did Thomson's.

ATOMIC DISINTEGRATION

A little way back, we mentioned the parentage of radium and suggested that its mystery might be cleared up. A knowledge of it was found to involve an investigation of the atomic disintegration of the top-heavy and unstable radioactive elements. In selecting uranium for his experiments, Becquerel had unwittingly seized upon the original progenitor of all the radioactive tribe. That it gave off these peculiar kinds of rays, there was no doubt. This had been the initial discovery in this virgin field. Of the work required to establish its ancestral claims, Rutherford has said, "The search for this elusive parent of radium has been one of almost dramatic interest, and illustrates the great importance of the theory as a guide to the experimenter. . . . The most probable parent of radium appeared to be uranium, which has a period of transformation of the order of 1000 million years. If this were the case, uranium, initially freed from radium, should in the course of time grow radium, i. e., radium should again appear in uranium. This has been tested independently by Soddy and Boltwood, and both have shown that . . . there is no appreciable growth of radium in the course of several years. . . . There is, however, another indirect, but very simple method of attack to settle the parentage of radium. If radium is derived from the transformation of uranium . . . the ratio between the amount of radium and uranium in old minerals should be a definite constant. This is obviously the case, provided sufficient time has elapsed for the amount of radium to have reached its equilibrium value. The constancy of this relation has been completely substantiated by the independent work of Boltwood, R. J. Strutt, and H. N. McCoy."* After much experimental investigation, in which the American physicist Boltwood largely figured, Rutherford could say, "We are able to link uranium, ionium, radium, and its long line of descendants, into one family, with uranium as its first parent."

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*_Nature_, Vol. 75, p. 54.

The reason for the negative result of Boltwood and Soddy, mentioned above, will be readily understood from the fact that the life cycle of uranium has been determined to be about five billion years. That is, it requires this prodigiously long period of time for half of any given quantity of the element to disintegrate, and an equal period for half of the remainder, and so on. Figuratively speaking, only once in an eon does a single atom of uranium arrive at the point of disintegration. However, in any mass of mineral containing the element some atoms are continually reaching this state of unstable equilibrium. And this disintegration consists always in the expulsion of alpha and beta particles.

Without describing the process in detail, let us picture uranium as tobogganing, during a period numbering countless millennia, from its initial state through a whole series of radioactive elements, including radium, to the element lead, and liberating a vast quantity of subatomic energy on the way. Some of the periods spent in the stations along the way are exceedingly brief, being reckoned in days and even minutes, while the hospitality of others is accepted for years and centuries.

We have just mentioned that metallic lead is the end product in this long series of atomic catastrophes. It soon became apparent, however, that radioactive lead, that is, lead from a radioactive source, differs in atomic weight from ordinary lead. For instance, the late Professor T. W. Richards, of Harvard, under whom it was once my privilege to study, found that the atomic weight of common lead is 207.19, of lead found in uranium ore 206.08, and of lead from an Australian mixture 206.34. Professor Richards said, "Shall we call these substances different elements, or the same? The best answer is that proposed by Professor Soddy, who invented a new name, and called them 'isotopes' of the same element." Thus, a new fact in chemistry and physics became known. The same element may exist in several isotopic states, differing from one another in atomic weight and occasionally slightly in physical properties, but indistinguishable by chemical test. This fact explained one perplexing difficulty. Why most of the elements should have atomic weights including a decimal, and not in each instance consist of a whole number, had been a puzzle. It now became plain. The atomic weights of the various isotopes of an element are whole numbers, but the proportions in which they are combined to form the element as we find it in Nature destroys this whole number value. For instance, lead is known to have isotopes with atomic weights of 204, 206, 207 and 208 respectively, and is believed to have two more with atomic weights of 205 and 210.

An interesting contribution to our knowledge of isotopes was made in the autumn of 1929, by Dr. Arthur S. King, superintendent of the physical laboratory of Mount Wilson Observatory, and Dr. Raymond T. Birge, professor of physics at the University of California. They announce the discovery of an isotope of carbon, having an atomic weight of 13, one more than the accepted number. Already, two other Californians, Dr. W. F. Glauque and Dr. H. L. Johnstone, both of the chemistry faculty of the University, had shown that oxygen is composed of a set of three isotopes. These findings are opposed to the conclusions of Sir F. W. Aston, who has done much work in this field. He has held that the atoms of elements like carbon and oxygen, whose atomic weights are whole numbers, can have no isotopes. Apparently, they can. If we could have a complete table of all the isotopes that exist, the number of elements would far exceed the accepted 92.

From estimates of the utmost reliability, based upon the known rate of radioactive decay of uranium, the highly interesting fact emerged that the crust of our earth, substantially as we know it now, is at least a billion years old, vastly older than the early geologists were willing to concede. As a result, the biologists, who were scraping along on the hundred million years doled out to them, may now have almost unlimited periods for their life processes.

THE BROTHERS OF THE ELECTRONS

The electrons had come of age and a quarter of a century had passed since they had taken their places as substantial members of the scientific community, and still their brothers of the positive faith had not been isolated. That positively charged particles existed, there could be no reasonable doubt. Yet they eluded every effort to detect their presence. It was believed that the nucleus, probably the most paradoxical unit of all creation, must contain, packed within its diminutive domain, these hypothetical members of the atomic world. Certain evidence, which we shall now briefly review, also pointed to a highly complex structure of this solar treasure-house.

As we have already seen, it had been shown that practically all of the mass of the atom is stowed within the nucleus. More important still, the disintegration of radium had been experimentally proved to yield alpha particles and a new element, niton. Now the alpha particles turned out to be helium atoms stripped of their two planetary electrons. That is, they were helium nuclei, bearing two positive charges and possessing an atomic weight of 4. The atomic weight of niton was found to be 222, while that of radium is 226. It will be seen that the subtraction of a helium nucleus from an atom of radium simply left a new element, whose atomic weight was as much less than that of the parent radium atom as the atomic weight of the lost helium nucleus. It was also perfectly clear that the helium nucleus was expelled from the nucleus of the radium atom, for there is where the mass of the atom is located. Any loss of atomic mass must draw upon the capital stock of the nucleus. There is no other source.

Then, too, there was another significant circumstance. Radioactive elements also expel beta particles. What was their source? Were they planetary electrons, stripped from the orbits about the nucleus, or did they come from the nucleus itself? Since the mass of an electron is practically zero, the loss of these electrons would be attended by no diminution of atomic weight. However, there was a telltale bit of evidence. It frequently happened along the highway of atomic disintegration in the radioactive series that a new element would appear having the same atomic weight as another, but a different atomic number. That is, the number of positive charges on the nucleus would be reduced by one. This is an excellent illustration of the fact, too, that the atomic number of an element is a much more significant constant than is the atomic weight. As in the case of isotopes, the atomic weights may vary quite widely, and still the chemical properties do not change and the physical properties only slightly. However, to return to the trail we are following, it was seen that, if a beta particle lost by a radioactive element were expelled from the nucleus, this would rob the nucleus of one negative charge, thereby being equivalent to increasing the positive charges by one and accordingly changing the atomic number. In other words, it became certain that packed within the nucleus were both alpha particles and beta particles. Radioactive disintegration, therefore, consisted in the disruption of the nucleus. Although this type of nuclear structure could not be demonstrated for any but radioactive elements, it seemed perfectly logical to assume that the atoms of all elements were built on a common plan. Perhaps, too, all would be found to be radioactive if our periods of observation could be sufficiently extended to detect it, which only serves to emphasize that human beings are mere ephemeral creatures of but the tiniest fraction of a cosmic moment.

Not until 1922 did the quest for the positively charged subatomic units corresponding to the electrons end in success. Then, Rutherford and J. Chadwick disrupted the nucleus of the nitrogen atom. The heavy artillery with which these invaders of time-honored preserves broke down the citadel of a once "impregnable" kingdom consisted of the alpha particles expelled from radium. Moving with a velocity of approximately 20,000 miles a second and possessing a considerable atomic mass, these are the most energetic missiles known to science. With them they shattered not only the nucleus of the nitrogen atom, but also the atomic nuclei of boron, fluorine, sodium, aluminum and phosphorus. Now comes the interesting revelation. In every instance, this disruption resulted in yielding a particle having precisely the same positive charge and atomic mass as the hydrogen nucleus and a lighter element. For instance, nitrogen gave hydrogen and carbon, aluminum hydrogen and magnesium, phosphorus hydrogen and silicon, boron hydrogen and beryllium, and sodium hydrogen and neon. Therefore, it became certain that the hydrogen nucleus was the long-sought companion of the electron. Its electrical charge, though opposite in sign, was precisely equal to that of the electron. It seemed reasonable to assume, too, that, like the electron, this twin brother should consist entirely of positive electricity,—that there should be no hard core or traditionary matter bearing an electric charge, but that the charge was the only constituent. This new particle was called the proton.

It seemed that matter had at last been tracked to its lair. Electrons and protons seemed to be the two ultimate units of fundamental reality. Just as Prout and other early scientists had imagined, hydrogen was a common constituent of all the elements. This was the primordial building stuff from which the primitive nebulæ had sprung. And both electrons and protons (sometimes called positive electrons) were wholly electrical in character. The status of matter had completely changed. Matter, mass and energy were inextricably interwoven. Old concepts were losing their original significance. A new physical world was emerging, the essence of which was electricity.

Until yesterday, scientists believed that in electrons and protons this quest for the ultimate in energy and matter had reached "journey's end." But with that propensity characteristic of scientific research for continually invading the snug retreats of speculative thought and upsetting completely the fancied security, the picture is already changing. At the Minneapolis meeting of the American Chemical Society in September, 1929, Dr. K. F. Bohnhoeffer, a youthful German chemist, with delicate physical apparatus demonstrated that the hydrogen atom has a twin. He did not split the atom, as was reported in some quarters at the time. According to press reports, he did produce evidence to show that the nuclear center is not single, but double. These two parts are in rotation. In ordinary hydrogen, such as we are accustomed to in a laboratory, the two halves of the atomic heart spin in the same direction, just as the two wheels of a bicycle do. However, in the new hydrogen, called para-hydrogen, they spin in opposite directions.

Dr. Hugh Taylor, of Princeton, calls this the "greatest scientific discovery of 1929." He says, "It opens up the way to finding an entire new species of molecule. It is the first proof of something forecast mathematically by the new wave mechanics. It means that our text books on physical chemistry will have to be rewritten."

One conclusion is inescapable: If the nucleus of the hydrogen atom is double, the same may be true of the nuclei of other atoms. May we not also suppose that the electron, too, will prove to be complex? Sir J. J. Thomson, several years ago, announced such a belief. To-morrow, it may be a commonplace of scientific discovery. Of theoretical interest only is this discovery of the young German chemist at present. It does not seem to have the remotest possibility of commercial application. Yet before this gets into print it may become a factor in television, talking movies or the price of gasoline. Certain it is that matter is vastly more complex than was ever imagined.

ROBBING THE X-RAY OF ITS MYSTERY

We have seen that until quite recent times the precise nature of the X-rays was unknown. We promised to tell the story of the discovery in this connection by the Swiss physicist, Laue, and for good measure we shall throw in a sequel, which in one important direction seems to push backward to their limit the frontiers of the universe.

Physicists imagined that X-rays were exceedingly short wave lengths in the ether—electromagnetic waves like those of light. However, they were believed to be about ten thousand times as small as the wave length of violet light, the shortest visible. This seemed to raise an insuperable barrier to any possibility of measurement. The most important means of doing this, and also of producing a spectrum, is by the use of a diffraction grating, discussed briefly in connection with the interference of light in the chapter on Newton. Such a grating consists of a piece of glass or a metal mirror, on which have been scratched fine lines exceedingly close together, as many as twenty or thirty thousand to the inch. The interference of light in falling upon this device produces a spectrum and, from the known distance of the line spacings, it is possible to measure the wave lengths. However, the determination of the estimated length of X-rays would require a grating with lines about a thousand times closer together than it is possible to rule them. That was the situation when Laue came upon the scene in 1912.

Laue knew that mineralogists had long regarded the regular form of crystals to be the result of the orderly arrangement of the atoms and the molecules composing them. Here seemed to be a vulnerable point of attack. Might not a crystal afford a ready-made, natural diffraction grating of the proper order of spacing? If the mineralogists were right, Nature had marshaled the atoms in regular sequence, tier on tier, rank, file and column. Laue put this hypothesis to test and verified it brilliantly. Not only did he show that X-rays are waves differing only in length from others in the long scale of electromagnetic vibrations, but he produced indubitable proof of the existence of atoms. X-rays were no longer a mystery, and atoms became as much a certainty as the stars of heaven. Furthermore, X-ray photographs showed the arrangement of the atoms and the structure of the crystal. New paths, theretofore undreamed-of, were immediately opened to the research investigator, and soon fresh conquests were being made. Therein lies the sequel mentioned above.

The man who utilized this discovery for the next strategic attack was Henry G. J. Moseley, a brilliant young demonstrator in physics at the University of Manchester and at Oxford, whose body stopped a Turkish bullet at the Dardanelles in the Great War, thereby providing one of the most tragic incidents in the annals of scientific men. Moseley conceived the idea of using the elements in succession as the target in his X-ray tube, upon which to receive the hail of electrons from the cathode. Just as before, the substance in crystalline form employed as the target served as a diffraction grating, and the resulting spectrum reflected from its surface could be photographed. To secure the X-ray spectrum of a gaseous or liquid element, some chemical compound of the element in solid form was used. By a process of elimination the part of the spectrum due to the element in question could be readily determined.

As a result of this work, a remarkable fact came to light. Not only could Moseley measure the lengths and frequencies of the X-ray waves, but he also found it possible to confirm the atomic numbers of the elements. As he passed from element to element, he discovered a definite, regular sequence in the succession of the X-ray spectra. It is put thus: "The square roots of the wave frequencies varied in progressive, stepwise fashion from element to element, giving a series of equal whole number steps that would, if complete, run approximately from 1 for hydrogen to 92 for uranium." If an element were missing, a conspicuous gap in the series unmistakably denoted its absence. Only two such gaps now remain to be filled. Thus, along one pathway of scientific discovery we are reaching the limit of possible advance.

THE ENERGY OF THE ATOM

Radioactivity had revealed the fact of subatomic energy. In the dissolution of the atom with the consequent formation of more stable systems, energy was released. Manifestly, energy in prodigious quantities was locked up within the atoms of the elements. Could it be liberated, controlled and harnessed to do the world's work? This question fired the imagination of layman and scientist alike. Speculation ran riot. Might there not be some secret spring, some sympathetic vibration, the discovery of which would make possible the tapping of this vast reservoir of electrical energy? Einstein had shown the equivalence of matter and energy, and had even worked out the precise mathematical equation governing the transformation. Of what value could this discovery be if it were not put to use? The only fly in the ointment seemed to be that the attainment of this goal might detonate all the atoms of the earth at once with a consequent celestial catastrophe of the first magnitude, and this earthly "vale of tears" would pass out in one grand blaze of glory. Happily, Millikan has recently assured us that the atoms of the elements have reached stable configurations. Although man may disrupt them with the liberation of subatomic energy, he will do so by "the sweat of his brow." This fancied triumph would cost more than it is worth. It would not be practicable. The dream of a workless world has thus been rudely shattered. It is not likely that any stock in such a project will soon be successfully floated in Wall Street. Dismal as the prospect may appear to be, man must still derive the wherewithal to carry on the industrial processes of the world from the time-honored sources of energy and power.

There is one aspect of this matter of much theoretical and practical interest. We shall refer to it briefly now and return to the subject again in a later chapter. Suppose an electron and a proton were actually to meet and coalesce. Since they consist of nothing but electric charges, as Eddington says, these charges would cancel, or neutralize each other, and we should have nothing left "but a splash in the ether which spreads out as an electromagnetic wave carrying off the energy." Mass would disappear and energy would take its place. This very process is believed to be taking place in the stars and nebulæ. It accounts for the celestial fires, which ceaselessly throughout the countless myriads of ages pour forth the energy which becomes the working capital of the universe.

Let us illustrate with a concrete example. We have seen that the alpha particle is a helium nucleus, and its atomic weight is precisely 4. It is believed that four hydrogen nuclei have been joined in its building. But the atomic weight of hydrogen is 1.008. There is no possibility of error in the determination of either of these numbers. They are perfectly correct. However, four hydrogen nuclei would give for the helium atom a mass of 4.032 instead of 4. What becomes of the extra .032 of mass? Evidently, it has disappeared. Has it been annihilated? No; it has been transformed from the state of matter to that of energy. And, trivial as this mass may seem, the quantity of energy liberated is prodigious. The energy in 0.032 of a gram of hydrogen (there are 28.35 grams in an ounce), converted into electric power at present rates would be worth nearly $100,000. Dr. Paul Foote, of the Bureau of Standards, says, "If the hydrogen in two teaspoonfuls of water be converted into helium, 200,000 kilowatt hours of energy is set free, representing $20,000 worth of electrical current, or ten thousand dollars to the teaspoonful."

Too bad that the key to this immeasurably vast source of energy seems to be beyond the possibility of human acquisition. However, we may comfort ourselves with the thought that we get this energy second hand in the electromagnetic waves which bridge the gulf of ninety-three millions of miles separating us from the sun. And of course it is rash these days for any one to say that anything is impossible. Still, the magnitude of the task involved in accomplishing this transformation is indicated in the immense quantity of energy liberated in the theoretical building up of helium atoms from hydrogen. That is the measure of the energy necessary to disrupt the helium nucleus—a circumstance which may well give pause to the boldest knight-errant of the scientific fold.

OTHER ASPECTS OF THE ELECTRON THEORY

The electron theory, so illuminating in the light it had shed upon a multitude of problems, also seemed to offer a clue to the explanation of magnetism. We have seen that a revolving electron possesses a magnetic field, and within the atoms are unquestionably such revolving units. All the known magnetic phenomena could be readily interpreted upon this basis. Furthermore, we recall that Faraday had in 1845 shown that magnetism, while preeminently a property of iron and to a lesser extent of cobalt and nickel, is nevertheless a universal property of all matter. In 1915, Einstein, too, gave a confirmatory proof of this electron conception. He saw that a revolving electron should act as a tiny magnet and at the same time possess inertia. Such a revolving body must have the inertial properties of a spinning top. In other words, it must be a tiny gyroscope. If the magnetism were reversed, this would mean a reversal in the direction of revolution of the electrons. It occurred to Einstein that if he were suddenly to reverse the magnetism of a soft iron rod, the combined inertial effect, or kick, of all the electrons would produce a momentary turn of the rod. This experiment was tried by De Haas, and the prediction was fulfilled, thus giving experimental evidence of the electron theory of magnetism.

Then, too, the electron theory has scored another success, which has an important bearing on the source of magnetism. In 1896, Pieter Zeeman, of the University of Amsterdam, made a discovery which has ever since been known as the Zeeman effect. As is well known, every element in the state of incandescent gas or vapor gives, when viewed with the spectroscope, a characteristic bright-line spectrum. That is, one sees a series of bright lines occupying a perfectly definite position in the spectrum and duplicated by the bright-line spectrum of no other element. Now Zeeman discovered that if the space occupied by the incandescent substance were subjected to the influence of a powerful magnetic field, each spectral line was split up into more than one line. In the simplest case, the line is split into two lines, one on each side of the original position. This indicated an effect of the magnetic field on the electrons. The explanation seems to be this: the effect of the outside field is to increase the speed of some electrons within the atom and to decrease the speed of others. Whereas, waves of one frequency, or rate of vibration, were being given out in the absence of the magnetic field, in its presence waves of two different frequencies appear. This accounts for the observed effect and incidentally gives support to the electron theory.

H. A. Lorentz, professor at the University of Leyden and often called the father of the electron theory, used the Zeeman effect to calculate the mass of the electron and showed that the disturbances observed in a magnetic field are in precise agreement with the theoretical. Lorentz needed a universal medium for his theory, and so he adopted the ether. However, he insisted that it be regarded as stationary under all circumstances.

In 1923, Millikan was awarded the Nobel Prize in physics for measuring with the utmost precision the exact charge which an electron bears. It was an extraordinary piece of research, and in speaking of it, he said, "He who has seen that experiment, and hundreds of investigators have observed it, has literally seen the electron. . . . The electron itself, which man has measured in the manner just described, is neither an uncertainty nor an hypothesis. It is a new experimental fact that this generation in which we live has for the first time seen, and which any one who wills may henceforth see." In this same address, this distinguished American physicist also said, "Electrons of both the positive (protons) and negative variety are then merely observed centers of electrical forces. . . . Further, since Rowland proved years ago that electrical currents are simply electrical charges in motion, the proof that electrical charges are built up out of discrete electrical particles, electrons, carries with it the proof that electrical currents such as pass through incandescent lamps consist merely in the drifting of numerous swarms of these electrons through conductors."

Dr. Arthur H. Compton, another eminent American physicist and Nobel Prize winner, in writing for the *Scientific American,* said: "The story is told that toward the close of the 19th Century one of Lord Kelvin's students approached him with the question, 'What do you think of this new theory that the atom has structure?' 'What!' said Kelvin, 'the atom has structure? The very word atom means the thing that can't be divided. How then can it have a structure?' The insubordinate youth is said to have replied, 'That shows the disadvantage of knowing Greek.' "

I hope this experimental fact and theory regarding the nature of things is not all Greek to you.

CHAPTER VII

A Topsyturvy World

UPSETTING ESTABLISHED IDEAS—AN ANCIENT DISPUTE—TWO RIVAL THEORIES—AN ILLUSTRATION—EARLY DISCOVERIES RELATING TO PHOTOELECTRIC EFFECT—FACTORS GOVERNING MAGNITUDE—EFFECT OF X-RAYS ON ELECTRONS—A CLASH WITH ACCEPTED PRINCIPLES—PLANCK AND THE QUANTUM THEORY—EINSTEIN'S EXPLANATION—A NEW VIEW OF THE NATURE OF LIGHT—A DILEMMA—LIGHT PHOTONS—ATTEMPTS TO MEASURE THEM—FLUORESCENCE—ITS EXPLANATION WITH AID OF QUANTUM THEORY—PARABLE OF THE PEBBLE—PHOTOELECTRIC CELLS AND TALKING MOVIES—RIVAL THEORIES FROM OTHER ANGLES—QUANTUM THEORY AND THE ATOM—INADEQUACY OF RUTHERFORD MODEL—THE BOHR ATOM—APPLICATION TO HYDROGEN ATOM—WHAT BOHR'S MODEL ACCOMPLISHED—THE BALMER FORMULA—THE BOHR ATOM AND EINSTEIN'S THEORY OF RELATIVITY—SOMMERFELD'S MODIFICATION—NEW LIGHT ON THE ELECTRON—ELECTRONS HAVE CHARACTERISTICS OF WAVES—DISCOVERIES OF DAVISSON AND GERMER—X-RAYS BEHAVE LIKE PARTICLES—ANOTHER DILEMMA—THE LATEST VOGUE IN ATOMS—THE SCHRÖDINGER ATOM—ATOMS OF THE CHEMIST—TOPSYTURVINESS ONLY APPARENT.

The scientific world of a generation ago had just succeeded in nicely putting its house in order—polishing the floors, dusting the furniture, arranging the bric-à-brac and getting everything in its proper place—when along came a hurricane of new discoveries, setting all in a flutter and disarranging the scenery in general. With the passing of the intervening years, this topsyturvy condition has seemed to grow worse—not better. The ether, the mainstay of a score of theories, appears to be slipping from its moorings. Waves with nothing to wave, the transmission of energy with nothing to transmit it, the existence of electrons and protons with nothing from which to fashion them, the fact of motion with no absolute medium of reference by which to measure it—all this is much as though the movement of a watch had mysteriously disappeared, leaving only the ticks.

We have just been establishing the electrical nature of matter, but no one has the slightest inkling as to what electricity is. We understand much regarding its behavior, but its innermost self is as dark a mystery as ever. If you have a luminous wrist-watch, examine it in a darkened room with a strong magnifying glass. The uniform glow appearing to the naked eye now becomes a myriad of minute flashes, each visible for an instant, and then vanishing. You are witnessing the impact of alpha and beta particles shot from radium atoms. These are tiny bundles of electricity, of which we know much, but not their very selves.

Much more of a mystifying nature in this topsyturvy world awaits explanation. Light seems to be a manifestation of both waves and particles. So do electrons. The impacts of X-rays are producing an astounding phenomenon. The picture of a planetary atomic system is dissolving. In its place, we see a quivering ball of electric energy—shadowy, vague, indefinite, but slowly taking shape. What the newest mode of the atom will be to-morrow, no one knows. All this, not to mention the paradoxes of relativity, is raising hob with scientific orthodoxy. Dilemmas, apparently irreconcilable phenomena, are the order of the day. There is no lack of interesting variety in this scientific movie. However, disturbing, perplexing, baffling as these diverse findings are, no one doubts that harmony will ultimately emerge. The utmost confidence in the integrity of the universe prevails. Belief in the irrationality of Nature has not yet become the fashion of the hour. Scientists still have faith that we live in a cosmos, and not a chaos.

Let us look at one small corner of this mystifying realm, and if it does not appear too forbidding, we may explore further. Possibly, the easiest avenue of approach will be through the reopened breach of an historic dispute. You will recall that Newton contended for the corpuscular theory of light. That is, he pictured light as a form of energy consisting of minute particles, or tiny darts, fleeting through space with tremendous velocities. For the explanation of some phenomena, he did, too, think of this movement as being in the form of waves. Although these two conceptions mixed no better than oil and water, the facts of observation sometimes seemed to demand both. How well he was diagnosing the precise predicament in which scientists would find themselves two centuries in the future, he never knew. As we have seen, the wave theory swept the stakes. It vanquished the corpuscular theory completely. In the snug physical world of yesterday, the wave theory met every need. More, it appeared to be indispensable to an understanding of things as they were, and it does yet. That is the trouble. We can not dispense with these waves, even if there is nothing left to wave, and yet they are at swords' points with another theory, equally authentic and well substantiated. Physicists are endeavoring to compose the conflicting aspects of the rival theories and to prevent a permanent break in diplomatic relations, but as yet neither lasting peace nor truce looms on the horizon. Let us look at the new theory and the facts supporting it.

Suppose you were to drop a pebble into a lake from a height of sixteen feet, sending out, of course, a series of ripples in every direction. At the distance of a few hundred feet, you know these waves would have practically spent their energy. What would be your astonishment, however, to discover that one of these nearly de-energized ripples, in chancing to strike another pebble precisely like the one that you had dropped, should hurl this pebble vertically into the air to a height of sixteen feet, the same distance from which you had dropped the first? I imagine that you would have no doubt as to the topsyturviness of your particular location in this universe of time and space. If such inconsiderate happenings should persist in recurring, you might easily believe yourself the victim of a mysterious nightmare, or find yourself applying for admission to an insane asylum.

And yet, that is precisely similar to what we find is happening in the physical world. The feat just described is not a whit more remarkable or impossible than what occurs when an ether wave falls upon a piece of metal. To get this bona fide circumstance of Nature straight, suppose we review briefly a bit of its history. You have not forgotten the experiments of Hertz in 1887, in which he established experimentally the theory of Maxwell. In the course of them, he happened to let ultraviolet light fall upon the spark gap in the copper ring he used as a detector. To his surprise, he found that in some way the voltage necessary for the passage of the spark had been decreased. We know now that these ultraviolet waves had ionized the atoms in the molecules of air. That is, they had set electrons free, thus increasing the electrical conductivity of the air. At that time, however, the electron had not been discovered. This effect has since been called the photoelectric effect, and we have many examples of it.

Another experimenter, Hallwachs, began a thorough investigation of this whole phenomenon. For one thing, he carefully cleaned a zinc plate and electrically insulated it. In other words, he mounted it so that any electric charge which it might receive could not escape. Then, he allowed ultraviolet light to fall upon the plate. Gradually, the plate acquired a positive charge, which increased the more intense the radiation and the longer the light was permitted to fall. What was happening? Clearly, one of two things. Either the plate was receiving positive electricity, or losing negative. To determine which, Hallwachs threw the ultraviolet rays upon the plate again, having first given it a negative charge. The negative charge soon disappeared, and a positive one took its place. It thus became perfectly clear that these rays dislodged electrons from the atoms of the metal, leaving them with an excess of positive electrification. We know now that the atomic nuclei had been robbed of their full quota of planetary electrons.

Many other metals exhibited this same effect. Further study showed that a number of factors entered into its magnitude. It depended upon the kind of metal, but more important was the kind of radiation thrown upon the metal. Red and yellow light had little influence, but blue light, ultraviolet light, X-rays and the gamma rays were prolific sources of this photoelectric effect. Whatever the radiation, it soon became evident that two properties dominated the situation—the intensity and the frequency, or the rate of vibration. And right here came the astonishing revelation. The intensity, by which in the case of ordinary light we mean the brightness, seemed to influence only the number of electrons released. The more intense the radiation, the larger the number of electrons shot out from the metal. The frequency determined the velocity with which they sped away. The higher the frequency of the waves, the speedier was the getaway. Let us get the full significance of this. No matter how feeble the radiation might be, the velocity of the departing electrons was just as large as though the intensity had been many times as great. Not so many electrons would be dislodged, but the energy with which they left would be as great as though the intensity had been of a high degree. A very feeble blue light would release electrons with precisely the same energy content as an exceedingly intense blue light. The number of electrons released would be smaller. That would be the only difference. And ultraviolet light, that is, light of shorter wave length and consequently higher frequency than blue light, no matter how feeble it might be, would liberate electrons with a higher velocity and larger energy content than the most intense blue light possible to obtain.

Now this was contrary to every criterion of the classical physics, utterly repugnant to common sense, and yet an undeniable fact—an additional bit of evidence of the topsy-turvy state toward which the once eternal verities of science seemed to be rapidly tending. It was in illustration of this situation that I told you the parable of the pebble. However, truth is always stranger than fiction, and therefore an example from the realm of reality will be more to the point.

We have seen that X-rays are produced by the bombardment of a metal target inside a cathode ray tube by swiftly moving electrons shot out from the negative terminal, or cathode. The swifter the speed of the electrons, the greater the force of the impact and consequently the shorter the wave length, or the higher the frequency, of the X-rays emitted. Now we shall let these X-rays travel through space and strike upon a metal, just as we have allowed other light waves to do. Here comes the paradox. A ripple sent out from the X-ray tube, no matter what its intensity may be, will jerk loose an electron from the piece of metal and hurl it forth with precisely the same velocity that the original electron producing the ripple in the X-ray tube possessed. The more intense the X-rays, the larger will be the number of electrons released, but the speed with which each particular electron will flee away will be identical with that of the electron that produced the disturbing X-ray ripple.

This fact of experimental physics is precisely analogous to the hypothetical case of the pebble. To make the comparison complete, we should add that if the intensity, that is the displacement of the water particles from their positions of rest, were large, more pebbles would be hurled into the air, but the height to which each would rise would be just sixteen feet, provided the frequency, the number of waves per unit of time, were the same. The feeblest sort of a water wave of this frequency would have the same effect. No wonder many felt that the solid foundations of the physical world were slipping from beneath their feet. Yet, it was the stern reality of truth. There was no difficulty about measuring with great exactness the speed of the electron in the X-ray tube before impact, the frequency of the resulting waves and the speed of the released electron. No physicist questioned the accuracy of these results. The only disquieting feature was the violence that they apparently did to accepted principles and the necessity for finding an explanation, at once adequate and in harmony with other equally authentic phenomena. That was the conundrum. Let us see where the trail of research has thus far led.

Einstein was the volunteer from the ranks who suggested a way out of the difficulty. To do so, he made use of one of the most revolutionary doctrines in modern physics. Some even regard it as of more significance than the far-famed theory of relativity. Certainly, it is of much more practical importance. This new feeler, reaching into the unknown, was put forth by Max Planck in 1900 as a means of explaining certain perplexing facts regarding the distribution of energy in the long gamut of electromagnetic vibrations, facts which appeared to be a total mystery on the basis of the wave theory of light. It is known as the quantum theory, and its distinguishing feature is the assumption that energy, like matter, is atomistic. That is, energy is put up and sent forth in small bundles, or packets. Scientists sat up and rubbed their eyes. Here was something, in a thinly disguised form, surprisingly similar to Newton's ignominiously defeated corpuscular theory of light. But it worked beautifully, and so met the supreme requirement of a scientific theory. Whatever the imperial scientist needs in his business, he will invoke. To-day, quanta of energy seem to be almost as firmly intrenched in the terrain of physics as are atoms, electrons and protons.

A unique feature of these atoms of energy is the fact that they are not all of the same size. Unlike electrons and protons, their energy content is not invariable. The greater the frequency, or higher the rate of vibration, the larger the amount of energy in one of these quanta. The magnitude of a quantum of X-rays, for instance, is much larger than that of a quantum of ultraviolet light. However, Planck worked out a factor, known as Planck's constant, such that the product of this constant by the frequency of the particular kind of electromagnetic waves under consideration will give the value of the quantum in any case. Thus, if we call the quantum of energy of red light 1, that of violet light will be approximately 2, ultraviolet light 8 and X-rays 8000. The value for gamma rays of radium will be still higher, and for Millikan's cosmic rays very large. However, you do not need to burden your brain with these barbarous facts. Forget them as fast as you like. I simply had to tell them to you to keep the record straight.

Just a word about Max Planck. He was born at Kiel in 1858. For years, he studied in Munich, and afterward spent one year in Berlin, where he attended lectures by Helmholtz, Kirchhoff and others. When thirty-one, he succeeded Kirchhoff at the University of Berlin, one of the most important posts in Germany. Two years before the Great War, he became permanent secretary of the Prussian Academy of Sciences. In the years to come his name will undoubtedly be placed with those of Faraday, Maxwell, Thomson and Einstein.

Now let us come to the contribution of Einstein. He saw the utter futility of trying to explain the photoelectric effect on the basis of the wave theory. It was manifestly impossible to account for these stunts in that way. Waves, in which the energy is uniformly distributed over the surface of a sphere, could not produce them. However, in the quantum theory, he saw a way out. He conceived of light or X-rays as moving in particles. These particles are now called "photons." They seem fairly well destined to take their place alongside of electrons and protons as one of the three fundamental entities of this universe.

The new picture of what happens in producing the photoelectric effect is this: The electron shot from the cathode of the X-ray tube strikes the target, its energy of motion there being transformed into a photon, or particle of X-rays, which travels with the velocity of light to the metal upon which it is to produce this effect. There it gives up its energy to one of the electrons in the metal, hurling it forth with a velocity, and therefore with an energy of motion, equal to that of the original electron in the X-ray tube. Clearly, this hypothesis can account for the observed facts. If all the energy in the first electron is converted into a photon, or small bundle of energy, and this photon succeeds in transmitting its cargo intact, without loss, to an electron of the metal, precisely the effects which are observed to occur would occur. There seems to be no loophole. This theory is water-tight. But it appears to be hopelessly at odds with the wave theory. In order to understand the propagation of X-rays and of light in general, electromagnetic waves are indispensable. Such phenomena as diffraction and interference of light are totally inexplicable by the quantum theory. So, too, are refraction and dispersion. The wave theory explains them perfectly. What shall we do about it? Find a solution, of course. That is what keeps science interesting and free from monotony. It is something like the situation in which a novelist finds himself when he has allowed his characters to tie things up into a hard bow-knot, from which he must extricate them. Suggestions are already being made. We need not fear,—the sun will shine once more.

Thus the scientific world seems to be shut up to the conclusion that both Newton and Huyghens were right. On Mondays, Wednesdays and Fridays, the wave theory wields the scepter, and on other days a modified form of the corpuscular theory holds forth. As one scientist says, he carries one theory in one vest pocket and the other theory in the opposite pocket. When he is dealing with one kind of phenomena, he conscripts the wave theory. When the tables are turned, he seeks the assistance of the quantum theory. But the original excitement is wearing away; it is getting about time, possibly before this book gets into print, for some genius to make the whole thing clear as day—to discover the underlying principle that spells unity and harmony. As Dr. Paul Heyl suggests, "undoubtedly the conflict between the quantum and the classical theory of radiation will be ended by the attaining in time of some broader concept, of which these two opposing theories will be seen to be special cases."

How big is a light photon? The attempt to visualize it has proved to be extraordinarily baffling. Silberstein, an American physicist, has suggested that it might be in the nature of a dart, possibly two or three feet long. Lorentz of electron fame showed that certain experiments of Michelson's on the interference of light call for a quantum about six feet wide. It might, therefore, be in the nature of an oblong sheet. Still, we must think of this "atom" of energy as entering the pupil of the eye or invading the stronghold of a metallic electron, being absorbed completely in the process, and all in an unimaginably small fraction of a second. Surely, this aforementioned topsyturvy condition of the scientific world is not abating. Instead, it seems to be tending somewhat rapidly toward a delightful state of bewildering perplexity.

In all seriousness, however, Dr. Ernest O. Lawrence and Dr. J. W. Beams, of Yale University, have devised an ingenious method of measuring the lengths of light flashes, or something approaching these light beam quanta, much as a meat-cutter slices sausage. Of this experiment, in the *Scientific American* for April, 1928, they say, "The importance of this simple experimental observation cannot be overestimated, for it definitely demonstrated that light quanta are less than a few feet in length and probably occupy only very minute regions of space. The experiment also showed that an electron absorbs enough energy in one thousand millionth of a second to fly out of a metal with a terrific velocity. This result is in accord with very recent theories of light. Dr. W. F. G. Swann, Professor J. C. Slater and others have a short time ago suggested that light has a dual nature; that there are both waves and quanta, the waves merely determining where the quanta may go. Quite independently, Sir J. J. Thomson also has developed this idea in considerable detail. According to Professor Thomson's views, the quanta are little rings of electrical lines of force, like doughnuts riding along on the waves, so that in the short flashes of the experiment described above there were many whole quanta able to knock out electrons from a metal—just as the experiment has demonstrated."

Thus we see that, although nothing very definite in the shape of an understandable coordinating theory has yet come to the fore, light shines through the darkness. The scientists are beginning to get out of the woods. And by the way, this glimmer of light is probably swarming with photons of energy.

FLUORESCENCE

For many years, it has been known that when invisible radiations are allowed to fall upon a variety of substances, they will glow, or fluoresce. Sometimes, the exciting radiation does not have to be invisible. Thus, if blue light is allowed to fall upon a piece of canary glass, a greenish color will be given out. We have seen, too, that one of the distinguishable characteristics in the early discoveries regarding cathode rays was their ability to excite fluorescence in the glass walls of the tube. When this luminous state continues for some time after the radiation producing it has been cut off, the effect is called phosphorescence. Unlike the photoelectric effect, these phenomena are due to the absorption of light energy and its reemission at a lower frequency. For instance, the greenish color of the canary glass is of a longer wave length, or what is the same thing, a lower frequency, than that of the blue light which excites the fluorescence. The visible wave lengths emanating from a Crookes tube are, of course, many times longer than the wave lengths producing them. This is all equivalent in principle to saying that if yellow light should fall upon a piece of white cloth, the reflected color would be red, or that if you should place your hand in the light from an incandescent bulb of green glass, it would appear to be yellow.

In the case of the photoelectric effect, a light photon falling upon a metal is entirely absorbed by an electron, which is immediately ejected with an energy content equal to that of the photon and also to that of the original electron which produced the photon. At least that seems to be true of photons produced by X-rays, the frequencies of which are relatively high. With fluorescence, the effect is different. The energy of the photons is not absorbed and then reemitted as projected electrons, but there results a radiation of lower frequency, low enough to be visible to the human eye. It is perfectly clear that the frequency radiated could not be higher than that of the initial radiation. If it were, more energy would be given off than is received. In other words, we should have the creation of energy, and the law of the Conservation of Energy would go glimmering. The lower frequency is entirely logical. However, it is difficult to explain on the basis of the wave theory of light. Let us see why.

Suppose we illustrate with sound waves. The phenomenon with which we are dealing here is precisely similar to that of an echo in sound. When you hurl your voice against a neighboring cliff, the reflected waves come back with the same frequency as those of the original sound. As you know, the pitch of the echo is identical with that of your voice. In the case of scattered X-rays, or of any of the rays producing fluorescent effects, the pitch of the radiation returned is lower than that of the original. If these fluorescent effects were due to the reflection of waves, the pitch of the reflected radiation should not be lower. Or else here is an exception to the general law of reflected waves, a thing difficult to believe. Einstein has shown, however, that the quantum theory gives a clear understanding of what happens.

To get Einstein's view, let us suppose that we have two billiard balls, one being several times larger than the other. Now, if the smaller ball strikes the larger one, it will be reflected, but a part of its energy will be spent in imparting energy to the larger. That is, the larger ball will suffer a recoil, and the smaller one will bounce off with less energy than it struck and at a slower speed. Just so, Einstein imagines, with a photon that strikes an electron. A part of its energy is expended in giving recoil to the electron and setting it into motion. Therefore, when the photon glances off and moves away, it possesses less energy than initially, which manifests itself in a lowered frequency. The pitch has been diminished. C. T. R. Wilson has been able to get photographs of electron trails in air, showing the paths of the recoiling electrons and confirming the picture. So accurate is this theory that it makes possible the calculation in advance of just what the radiated frequency will be, and the experiment corresponds with the prediction. So it happens that the quantum theory has scored an important success in the field of fluorescent phenomena. Why some substances should be fluorescent and others not, no one knows. The fluoroscope, used in X-ray work upon which to catch the shadow image, depends upon this principle. If it were not for this property, X-ray images could not be observed directly. Nearly all petroleum products, such as kerosene, vaseline and lubricating oils, fluoresce, giving a bluish effect. Clearly, fluorescence is quite different from reflection, and the wave theory offers no explanation.

Before leaving this subject, let us return for a moment to the parable of the pebble, or rather to its counterpart in photoelectric effects. The mystery as to why the second electron should be shot out with the same velocity as that of the electron whose impact on the target of the X-ray tube produced the light photon has not been entirely cleared up. The following explanation has been suggested: When the frequency of the X-ray radiation happens to be exactly the same as the natural frequency of the ejected electron, the energy content of the exciting photon is entirely transferred, and the departing electron must necessarily move away with the same velocity. Thus, it seems to be a case of sympathetic vibrations. As is well known, a note produced by a tuning-fork of one frequency will set into vibration another tuning-fork of the same pitch. In the case of the tuning-forks, not all the energy of the first fork is absorbed by the second. If it could be, the resonant note would be just as loud as that of the first fork. In the photoelectric effect, however, the transfer of energy is one hundred per cent. complete.

THE PHOTOELECTRIC CELL

On the morning of April 8, 1927, the papers throughout the country carried head-lines telling that on the previous day, Secretary Hoover, now President, and others speaking in Washington were seen as well as heard in New York. Television had passed from the realm of dreamland to that of actuality. Over the wires spanning the two hundred miles of intervening space flashed two distinct sets of electric impulses, one reproducing itself as speech, the other as light. The listener and observer in New York looked into a small translucent screen and thereupon saw his friend in Washington and at the same time heard his voice. He saw the movements of the lips, the smile and every detail of the face. In vivid fashion, this animated image gave the impression of a photograph come to life. On a larger screen, an audience of invited guests beheld the image of the distant speaker, and an amplifier enabled them to hear his voice. Wonderful! To be sure, but let us be reminded that this triumph would have been impossible without the photoelectric cell, depending, as its name indicates, for its operation upon the very effect which we have just been discussing. Suppose we get a glimpse of how it works.

In front of the speaker in Washington, we see a boxlike construction, with a square hole through the center and on either side the photoelectric cells, the electrical eyes of the invention. Behind the square hole is a perforated disk, through which shines a beam of light. As the disk rotates, this scanning beam of light moves to and fro horizontally across the speaker's face, working its way from top to bottom and then returning to the top. The entire scene is swept in less than a fifteenth of a second. Now the light from the face is reflected into the photoelectric cells. These are cells containing metals which are very sensitive to the photoelectric effect. As light falls upon the cell, it generates an electric current, and the amount of the current is proportional to the intensity of the light. The brighter the reflection, the larger the current. The light causes the metal in the cell to lose electrons, and as we have discovered, the stronger the light, the larger the number of electrons that are lost. This charges the metal positively, and in recovering its lost electrons a current will flow in the connecting circuit. Manifestly, the more electrons that are lost, the larger will be the positive charge and the stronger the current. It is at once apparent that the quantity, or intensity, of the light falling upon these cells depends upon the relative intensities of the light being reflected from the scene, in this case the speaker. The light portions will reflect much light, the dark portions little. Therefore, the current flowing from the photoelectric cells will vary precisely as the lights and shades of the object whose image is being transmitted. So sensitive are the cells, too, that they respond perfectly to variations in these reflections made at the rate of forty-five thousand a second. It has been determined that when light falls upon potassium metal, electrons begin coming off the surface in less than three billionths of a second later.

Of course, the current from these cells is exceedingly weak. It could by no means be transmitted just as it comes from them over the line from Washington to New York. But the matter of increasing its strength is easy. That is a commonplace of the radio art these days. Ordinary vacuum tube amplifiers magnify it five thousand million million times.

At the receiving end, this picture current, carrying the indelible impress of the lights and shades of the distant scene, is made to produce light effects. If light of variable intensity can be made to produce an electric current varying in the same way, the reverse process should also be possible, and it is. For this purpose, we must have the exact opposite of the photoelectric cell, something just as instantaneous in its action and just as sensitive in its response. The "neon tube" affords precisely these qualifications. The variable current, amplified to a high potential, is passed through a tube filled with neon gas at low pressure. This gas, one of the rare gases of the atmosphere and not long ago thought to be utterly useless, has the property of glowing when a discharge of electricity is passed through it. That is, the electrons get excited and throw off electromagnetic waves, or photons; it will not matter which in this case. The brilliancy of the glow depends upon the intensity of the discharge, and that in turn upon the variableness of the picture current. The result is a pulsating glow of light corresponding precisely in every detail to the lights and shades of the object whose image is being transmitted. This light is now passed through a perforated rotating disk, which is an exact duplicate of the disk at the sending end. Thus a pencil of light is made to play upon the receiving screen, precisely as the one in Washington did upon the speaker's face. A synchronizing current passing between the two stations keeps the motors which operate the disks running in unison.

We see that in their practical aspects these scientific phenomena are not so topsyturvy after all. It is only in the theories put forth to account for them that they play pranks with the gray matter in the brains of learned scientists. Few of us would agree with the distinguished mathematician who, in announcing a new theorem, exclaimed, "And thank Heaven, no possible use can ever be found for it."

The photoelectric cell is also the strategic element in the success of talking movies and the wireless transmission of photographs. Recently, it has been employed to measure the light of stars. A star image is focused on this electric eye, and the current produced gives a measure of the amount of light received. And this light, too, may have been a thousand years on the way.

THE RIVAL THEORIES FROM OTHER ANGLES

Dr. Arthur H. Compton has produced experimental evidence to confirm Einstein's theoretical account of the behavior of scattered X-rays when they rebound from electrons which they encounter. He finds, and proves by photographs, that the X-ray is scattered in a definite direction with respect to the recoiling electron, just as it should be if it is a particle. If, however, the X-ray is a wave, it should scatter in all directions. On the other hand, the interference experiments of Laue, in which X-rays were diffracted to produce atomic patterns of crystals and also to make possible a very precise measurement of the frequencies and wave lengths of X-rays, point with equal force to the wave theory conception of this highly penetrating form of energy.

There is no question whatever that X-rays, light rays and heat rays are alike the results of electromagnetic vibrations. If X-rays consist of particles, so must the others. They must all stand or fall together. Somewhere a reconciliation exists. As already indicated, one compromising view holds that the energy of the radiation is confined to the photons, or particles, and that the waves merely direct their course. Another pictures the radiation as consisting entirely of a true wave movement except in its action upon atoms and electrons. Then the energy assumes a granular state. Both waves and particles, the facts demand. Compton likens the combination to sheets of rain such as we sometimes see in a thunder-storm. The sheets correspond to the waves and the droplets to the energy particles. It is a hard nut to crack—one of the hardest that scientists have ever encountered.

Let us review briefly. Up to the time of Faraday, scientists had assumed the fact of action at a distance. Then the master of the Royal Institution showed by experiment that, in the phenomena of electromagnetism, the intervening medium must be considered. Maxwell advanced his theory of electromagnetic waves in the ether. Hertz proved their reality. The ether then seemed to be firmly established. It was continuous, the waves were continuous, and it was believed, or at least hoped, that matter would be discovered to consist of some continuous modification of the ether. Then came the discovery of the electron and the proton—nothing in each instance but a particle of pure electricity. An electric current became a flow of electrons along a conductor. Discontinuity was becoming the keynote in the interpretation of natural phenomena. In one important domain, however, continuity still ruled. Radiant energy was not atomistic. Then came the discovery of phenomena explainable only on the assumption of the quantum theory, with its photons, or discrete particles of energy. As we shall see, too, serious doubts were beginning to be cast upon the existence of the ether itself. Everything was in a turmoil. The order established by two centuries of painstaking research was vanishing, and the confusion was not to cease. Indeed, the world of scientific theory did seem to be topsyturvy.

THE QUANTUM THEORY AND THE ATOM

In the previous chapter we left the Rutherford atom with the hint that its stability was in a rather precarious state and its tenure of office likely to be brief. We are now ready to take up this thread of the narrative once more and to examine the difficulties confronting the planetary conception of atomic structure. Chief of these was the discovery that such an atom could not continue to exist. Had the universe been built from atoms fashioned after the Rutherford model, it would long since have ceased to be. We should not now be here to speculate on Einstein and relativity, the price of gas and the future of mankind. However, out of the ruins of what was once to be "a thing of beauty and a joy forever," a new model was built, and it embodied in its construction the principle of the quantum theory. But let us look first at the weaknesses of the old model. It will be much like going to the museum to look at the automobiles of yesteryear.

Now according to the accepted principles of electromagnetic phenomena as established by Maxwell, any change whatever in the motion of an electrically charged body is accompanied by a radiation of energy. And an electron is an electric charge itself. Whenever it undergoes any change in its speed or in the direction of its motion, it radiates energy. We saw that the periodic movement of an electron in its orbit about the positive nucleus would account for the production of electromagnetic waves. That is perfectly sound, but no more than a man can continue to spend money indefinitely unless he has an inexhaustible bank account, can this electron continue forever to emit electromagnetic energy, for we see that the electron is, at every point of its orbit, suffering a change in the direction of its motion. Furthermore, just as in the case of the moon, it is subject to an accelerated motion toward the nucleus. For an electron not to radiate energy, it would need to be either at rest or moving with uniform motion in a straight line. Neither could be true. In the one case the electron would fall into the nucleus with annihilation to itself and resulting chaos to the universe, and in the other any conception of an atom would automatically disappear.

The electron must, therefore, have a circular or elliptical motion about the nucleus. But it can be shown that its continual radiation of energy would result in a smaller and smaller orbit and a constantly increasing velocity of revolution. It would be simply a matter of time until the electron would be drawn into the nucleus, with the neutralization of the electric charge of each, the liberation of a large quantity of energy and the annihilation of the atom. That is, the atom could not exist on the basis of the Rutherford model.

Furthermore, there is another important feature to this affair. We have pointed out that an element in the state of incandescent vapor gives a bright-line spectrum. These lines are clear-cut, perfectly definite, and unduplicated by those of any other element. They are due to the periodic movement of the outer electrons in their orbits. If these lines are to be sharp, as they are, then the electrons can not be continually changing their velocities about the nucleus and the sizes of their orbits. If they did, there would be a continuous succession of such lines, and not the permanent positions which we find. Thus the lines were drawn closer and closer against this once promising conception.

That was the situation when the young Danish physicist, Niels Bohr, came upon the scene with a new atom model, which won for him the Nobel Prize and a distinguished place among the scientists of two continents. Let us get a picture of it.

Bohr, of course, accepted the standardized conception of a positive nucleus and planetary electrons. Indeed, experimental physics seemed to compel it. But he modified it, and therein lay the secret of his triumph. His revolutionary idea pictured the planetary electrons as revolving in fixed orbits of various diameters, but with a certain definite and invariable speed in each orbit. These speeds are proportional to the numbers 2, 4, 6, 8, et cetera, but within a given orbit the speed can be neither more nor less. There is no stepping on the gas to accelerate the motion. And there are no intermediate orbits between those fixed by the theory. Bohr determined that the diameters of the permissible orbits must be proportional to the squares of the ordinal numbers 1, 2, 3, 4, 5, et cetera. Thus the Bohr arrangement differs from the planetary system as we know it in astronomy, where it is entirely possible for an orbit to be changed to any conceivable extent by the application of the appropriate external force.

But it is in the radiation of energy that the Bohr atom departs radically from Rutherford's. We have seen that the latter ceaselessly radiated energy, and could not help itself. Bohr arbitrarily decreed that his atom should not do this. Thus, he deliberately violated all the accepted principles of the classical theories. His only excuse was that he needed to do so, in order to make his model work. Of course, this made it in a way a topsyturvy model, but what the empirical scientist needs he will have. An atom must in some manner radiate energy, else there would be no electromagnetic phenomena, no heat, light or spectra. Therefore, Bohr provided that an electron in one orbit might, in response to the proper external force, or excitement, jump from that orbit to an adjacent one in an instantaneous movement. That is, the electron would simultaneously disappear in one orbit and reappear in the other. In doing so, if the jump were from an outer to an inner orbit, a kick would be given to the ether and an electromagnetic vibration of definite frequency would be emitted. This produces a certain definite line in the spectrum of this particular kind of atom. In giving this kick to the ether, too, a quantum of energy is liberated. Thus, Bohr's atom is a quantum theory atom. It respectfully made its bow to the latest mode in atomic physics.

Suppose we illustrate the Bohr theory with its application to the hydrogen atom. To this atom, he assigned five possible orbits in which the solitary planetary electron might make its revolutions about the solar nucleus. The speed in the first orbit is about one-tenth that of light, and it becomes one-half, one-third, et cetera, of that velocity in the successive orbits, as the electron moves outward. If we have an atom with its planetary electron in the fifth orbit monotonously making its round of revolutions, an external stimulus of just the right intensity may cause this nuclear satellite to jump to the fourth orbit. In so doing, it gives out a pulse of light, producing a certain spectral line. Then, it may repeat the process, until the innermost orbit is reached, giving a kick to the ether with each jump. When the electron finds itself in this smallest orbit, it can pass outward again only by the absorption of energy. This may happen in various ways, as when light of just the same frequency as this electron makes in its jumps falls upon the gas. Ordinarily, hydrogen gas emits no light, as any one who has prepared it in a chemical laboratory knows. The electrons in the myriads of atoms are revolving in their respective orbits at definite speeds. There will be multitudes of atoms with electrons in each one of the five fixed orbits. To make the electrons jump from orbit to orbit, some external force such as heat or a discharge of electricity must act upon the gas. Then electrons are dislodged from their orbits, from the center outward. In hosts of them, the electrons are kicked entirely outside of the whole five orbital paths, leaving the nucleus temporarily abandoned, or ionized. Then, the reverse process begins, and the electrons start to regain their lost positions in the atomic orbits. This homeward march results in millions of ether kicks in each one of the four possible jumps. At any instant innumerable electrons will be making simultaneously the same relative move. Therefore, all the spectral lines appear together when this incandescent gas is viewed with the spectroscope. Since the electron radiates energy only during these jumps, the bright lines produced are definite and sharp. If no energy is received, no energy is lost. Thus, this atom might remain intact indefinitely. It is not subject to early annihilation as the Rutherford atom was. And this absorption and emission of energy are in definite small quantities, or in accordance with the quantum theory.

What had been gained? First of all, what has just been stated, namely, an atom that could survive, at least, if we grant the artificial assumptions that Bohr made. In speaking of this model, Dr. Paul Heyl says, "Imperfect as it must be admitted to be, the Bohr atom has proved itself a most remarkable practical success, especially in fitting the very complicated and somewhat irregular requirements of the periodic system of the elements. Here Bohr's theory progresses with a regular, measured tread, its pocket full of elements, dropping one element at each step into its proper compartment in the Periodic Law; and when it comes to that anomalous and closely grouped family of the rare earths, it pauses in its forward stride, drops each rare earth meticulously into its proper place, and then resumes its former measured tread, dropping elements at regular intervals as though there had been no interruption. Such procedure is more than uncanny; it is, as Whetham says, Satanic."*

And this atom has scored other no less notable successes. In particular, it for the first time explained a relationship which had been known since 1885, called the Balmer formula. Johann J. Balmer, a teacher in a girls' school in Basle, presented to the scientific society of that place in his sixtieth year a paper on the spectral lines of hydrogen. In this he showed that the frequencies of these lines could be represented by a certain very simple formula. He arrived at this formula by a wholly empirical procedure, and neither he nor any one else had the slightest inkling as to why it should be so. It worked, just as Bohr's atom did, and so it was accepted for what it was worth. But Bohr's quantum theory of the atom explained beautifully just why this formula should be true. Bohr showed that it was no accident. From his theory, by an entirely independent method of procedure, he was able to deduce the formula. That

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*From *Fundamental Concepts of Physics*, by permission of The Williams and Wilkins Company, publishers.

was the first great success to the credit of the new atom model and, however objectionable on some grounds this atom might be, there was no question that it represented some measure of truth.

In another direction the Bohr atom was no less successful. It proves to be an extraordinarily interesting bit of evidence, supporting alike the Bohr theory and Einstein's principle of relativity. We say that this new advance supported the Bohr theory. It did so, but with a modification which marked an important extension of it. Bohr had assumed only circular orbits for his electrons. It seemed quite possible, however, that they might be elliptical, like those for the planets of our own solar system. Arnold Sommerfeld, a brilliant researcher in this field, worked out the mathematical consequences of such a change in the orbital paths. It proved to be one of the most illuminating hypotheses in the recent history of physics. In their main outlines, the results parallel substantially those for a planet revolving about the sun, as developed by the principle of relativity. Let us anticipate this particular point of that theory by stating briefly the case for the planet Mercury, the only one in which the effects are large enough to permit of measurement.

Astronomers had known for many years that the orbit of Mercury was slowly shifting in the direction of the planet's motion to a larger extent than could be accounted for on the basis of the Newtonian Law of Gravitation. The shifting amounts to five hundred and seventy-four seconds of arc in a century, all but forty-two of which could be credited to the known gravitational influence of other planets. These additional forty-two seconds, however, represented a profound puzzle. Over and over the calculations had been made, and all sorts of theories had been proposed, but no solution appeared to be in sight. Then came Einstein with his theory of relativity.

Since the orbit of a planet is elliptical with the sun at one of the foci, the planet in its revolution will vary in its distance from the sun. This variation in distance will also cause a variation in the velocity of the planet in its orbit, being greater when the planet is near to the sun and less when it is far away. Now, as we have seen, the mass of a body, in accordance with the Einstein theory and also by actual experiment in the case of alpha and beta particles, increases with increase of velocity. This increase of mass in that portion of the planet's orbit in which it is nearer to the sun must manifest itself in an increased gravitational pull. Of course, it had been known since the time of Newton that the changing distance of the planet in its orbital motion causes the gravitational influence to vary. But here was an entirely new factor, that of varying mass, theretofore wholly neglected and never suspected. Einstein applied it and obtained forty-three seconds of arc as the additional shift in Mercury's orbit unaccounted for by other influences, which is exceedingly close to the traditional forty-two. This was the first great triumph scored by the Einstein theory of relativity.

Sommerfeld applied the same reasoning to the electron orbits of an atom, and with equal success. As indicated, he assumed elliptical orbits instead of circular ones, putting the nucleus at one of the foci. Thus, the speed of an electron in its orbit would be a variable quantity. Consequently, its mass would vary. This would cause a slow shifting of the orbit, just as in the case of Mercury. The actual motion of the electron would be the result of a combination of these two motions. The total effect in the case, say, of the hydrogen atom is to vary the frequencies of the electromagnetic vibrations emitted. This means that for each bright line in the spectrum there will also be two or three very fine lines quite close together. These are called the fine lines of hydrogen. Observation has shown that they exist, not only for hydrogen, but for helium as well, and in perfect accord with Sommerfeld's calculations. Thus, the relativity theory won again, and the Bohr atom received an important corroboration.

Still, striking as these successes were, the Bohr atom was bound to pass. The chief score against it was the way in which it played fast and loose with long-established principles regarding the radiation of energy, not, however, that this application of the quantum theory is necessarily wrong. Still, there is something not yet understood regarding the process. What steps are being taken to clear up the mystery, we shall see.

A NEW LIGHT ON THE ELECTRON

Nowhere is the topsyturviness of the present situation in many parts of the physical world better illustrated than in the new view of the electron. A generation ago it was shown to the satisfaction of every one that these units of negative electricity are particles. Like a hail of bullets on a rampart, they bombard the target in an X-ray tube. However, if light, long thought to be a wave movement, turns out to be particles with wave characteristics, why should it not be equally plausible to assume that electrons also partake of a dual nature? If light proves to be a "Dr. Jekyll and Mr. Hyde," why not electrons too? Thus thought the French physicist, de Broglie. Working upon this hypothesis, he calculated what the wave length of an electron should be when moving at approximately the average speed of those shot from the cathode of an X-ray tube. It was found to be about the same as the wave length of an X-ray. This was interesting, but more was to follow.

Gradually, it was discovered that X-rays and electrons have striking similarities. One of these is the matter of reflection. Suppose we etch a polished piece of steel with acid, thus bringing out a mosaic patchwork due to its crystalline structure. If ordinary light is thrown upon this surface at any angle, it will be regularly reflected, such that the angle of incidence will be equal to the angle of reflection. This means that the angle between the incident ray and a perpendicular to the surface at the point of incidence is equal to the angle between the perpendicular and the reflected ray. This law is also obeyed in the reflection of elastic balls, sound waves, radio waves and heat. However, if X-rays are thrown upon the surface of such a piece of etched steel, they will be scattered in all directions. Their wave lengths are too short, so much so that the molecules in the crystal structure offer a rough surface to them. Consequently, the X-rays glance off in every direction from this higgledy-piggledy array of reflecting surfaces. Another factor in this effect is the fact that the X-rays penetrate the metal to a certain distance. Therefore, their behavior is quite different from that of the long waves of ordinary light. Here we are talking of waves of light, when we have just seen that light is more than likely a composite array of particles of energy. But in a topsyturvy world anything is permissible.

It has been found that X-rays can be regularly reflected, if the beam is confined to the face of a single crystal. They are not then scattered as before. But the angle of incidence must be just right. With ordinary light, the angle of incidence may be anything. Not so with X-rays, but what the particular angle of incidence must be in any given case depends upon the wave length of the X-rays and the character of the crystal.

Now Davisson and Germer, two physicists of the American Telephone and Telegraph Company, through a lucky accident made a discovery showing a close relationship between electrons and X-rays—at least in their behavior. They were bombarding with electrons a polished piece of nickel in a vacuum tube. Just as in the case of X-rays, the electrons were being reflected in all directions, that is, scattered. Then came the accident. The glass bulb broke, and the inrushing air formed a film of oxide over the hot surface of the metal. To remove the oxide, they heated the nickel in a stream of hydrogen, which unites readily with oxygen. When they set their apparatus up again, to their surprise they found that the electrons were being reflected in regular fashion.

The explanation is this: The heat treatment had increased the size of the crystals. So large had they become that the reflection was much like that of small rubber balls from a large smooth surface. By special heat treatment, Davisson and Germer then produced a still larger crystal of nickel and repeated the experiment with identical results. The reflection was precisely like that of X-rays from crystal surfaces. Similarly, the angle of incidence had to be just right before reflection would occur, the speed of the electron seeming to determine this. The speed of an electron appears to correspond to the wave length of X-rays, the higher the speed the shorter the length, or whatever corresponds to it. Thus, electrons had been shown to have characteristics precisely similar to those of X-rays, long known to be electromagnetic waves. In other words, an electron appears to be a little bunch of waves. Surely, topsyturvy seems to be no misnomer for things in this particular neck of the scientific woods. Waves are particles, and particles are waves.

We saw in the previous chapter how scientists hailed the triumph of Laue in obtaining X-ray spectra, or diffraction patterns, of crystals, thus killing two birds with one stone. He gave evidence unimpeachable of the existence of atoms and molecules, and at the same time was able to measure the wave lengths of X-rays. That X-rays were waves, there could no longer be any doubt. Now G. P. Thomson, son of Sir J. J. Thomson, is producing the same kind of diffraction patterns by passing streams of electrons through crystals. If X-rays are waves, so must electrons be too. The evidence for one is just as good as it is for the other.

Such is the situation as it appears to-day. Paradox, dilemma or whatever you choose to call it, these are the facts with which the scientist must deal, and we may be perfectly sure that wherever the trail of truth leads he will follow. No preconceived notions, no prejudices of any description will influence his judgments in the slightest degree. His only criterion is truth.

THE LATEST VOGUE IN ATOMS

A short time ago, an American newspaper in an article on the atom said: "The next time you go shopping for atoms insist upon the Schrödinger sort. Don't let the dealer fool you with any last year's Bohr stuff. And after this keep a sharp eye out for changes in fashion."

Let us emphasize, however, before discussing this new atom that, despite the facetious tone of the foregoing, the basis for every atom model has been experimental facts. When one has served its usefulness and new discoveries point to a better and truer conception, the scientist discards the old as readily as he would a threadbare coat or a worn out pair of shoes. That is the glory of his method and the foundation of his progress.

But to proceed: This new idea of the electron was bound to have an influence upon the conception of the atom. Out of it has grown Schrödinger's wave atom. Schrödinger is an able young Austrian physicist who has done most to paint the latest picture. This model is an infant of four years, and is not yet very well understood even by the scientists. The forerunner in fashioning it was Louis de Broglie. He tried to apply the Einstein theory to the Bohr atom in an even more thoroughgoing way than Sommerfeld had done. The only way in which he could make the relativity equations fit was to assume that the electrons in their revolutions about the nucleus are accompanied by waves. This is a most significant circumstance, for we have just seen that electrons behave as though they are waves. Pretty soon it began to appear that the very rapid motion of an electron in its orbit made necessary a complete series of waves all the way around. De Broglie's calculations showed, too, that the only possible orbits for these wave trains were those of the Bohr atom.

The next step was for Schrödinger to show that we might dispense with the electron entirely; and yet something, an actual entity, corresponding to the electron exactly as it has been previously described, is emitted from the atoms of radioactive elements and by the cathode of a Crookes tube. The electronic conception of the distribution of energy in the atom has been superseded by that of an atomic sphere in which the electric charge is spread out, with the nucleus at the center, described by one as "an electrical hole in the center of the aura." Instead of electrons in rapid motion, we have the intensity of this diffused charge fluctuating at different points at different moments of time. This variation of the intensity of the charge produces electromagnetic waves, just as the periodic revolutions of the electrons in the Rutherford model did or as did the jumps of the electrons in the Bohr atom. When an atom throws off an electron, as in the case of radioactive atoms, it does so in the form of a tiny bunch of waves.

Again what has been gained? An atom which will do all that the Bohr atom did and more, for it will radiate energy without doing violence to the established principles of the classical physics. It is by no means perfect; this new wave conception is not yet clear. It is in a nebulous state of evolution. Nevertheless, it registers progress. In the points of varying intensity of the electric charge, we have something resembling the quanta of energy. But this atom has, so to speak, only just made its bow to the elect of the scientific world, and we must wait with patience to know what its future will be.

In one important respect, none of this brood of atoms meets requirements. They do not help the chemist greatly to solve his problems of chemical action. And the atom is the chemist's practical working unit. Chemical behavior should certainly come within the scope of a theoretical atom's operations. Because these thus far do not, the chemist has constructed atoms of his own, each performing beautifully the thing for which it was designed. And so the work goes on. Sometime, we may be perfectly sure, will come the master architect who can build a structure that will satisfy every demand of physicist and chemist alike. Until then, we shall make the best progress possible, profiting in each new advance by the work that has gone before. Each succeeding discoverer will stand on the shoulders of his predecessors.

And now we shall leave this part of the topsyturvy domain. In doing so let us emphasize that the topsyturviness is not real. It is only apparent, because we do not yet know the whole truth. With the larger vision that is bound to come, all will be made plain. The marching song of the new order will be the harmony of all creation.

CHAPTER VIII

RELATIVITY FOR EVERYBODY

RELATIVITY V. COMMON SENSE—MEANING OF RELATIVITY AS OPPOSED TO THE ABSOLUTE—EXAMPLES OF RELATIVITY—MICHELSON-MORLEY EXPERIMENT—MICHELSON—QUESTIONS RAISED BY MICHELSON-MORLEY EXPERIMENT—DIVERGENT VIEWS REGARDING THE ETHER—FITZGERALD-LORENTZ EXPLANATION—COMING OF EINSTEIN—PRINCIPLES OF SPECIAL THEORY OF RELATIVITY—LIMITING CHARACTER OF VELOCITY OF LIGHT—ILLUSTRATIONS—RELATIVITY OF ALL MEASUREMENTS—EXAMPLES—RELATIVITY OF TIME—DEPENDENCE ON VELOCITY OF LIGHT—RELATION OF MASS TO VELOCITY—EFFECTS UPON TIME-KEEPING QUALITIES OF CLOCKS AND UPON LIFE PROCESSES—BEARING UPON THE RELATIVE VALUES OF PHYSICAL MEASUREMENTS—GENERAL THEORY OF RELATIVITY—INDISSOLUBILITY OF TIME AND SPACE—TIME-SPACE COMPLEX UNPICTURABLE—THE MEANING OF THE TERM INTERVAL—OTHER GEOMETRIES THAN EUCLID'S—CURVED SPACE—EINSTEIN AND GRAVITATION—SIMILARITY BETWEEN GRAVITATION AND INERTIA—ARTIFICIAL CREATION OF A GRAVITATIONAL FIELD—NEW CONCEPTION OF GRAVITATION—EINSTEIN'S PREDICTIONS AND THEIR VERIFICATIONS—DISCREPANCIES IN ORBIT OF MERCURY—DEFLECTION OF RAY OF LIGHT—ECLIPSE EXPEDITIONS—SHIFTING OF THE SPECTRUM—A FINITE UNIVERSE—EINSTEIN'S LATEST ANNOUNCEMENT—THE MAN HIMSELF.

BERTRAND RUSSELL in *The A B C of Relativity* says, "It is true that there are innumerable popular accounts of the theory of relativity, but they generally cease to be intelligible just at the point where they begin to say something important." And this calls to mind the story of a man who went to court to secure a divorce. When asked by the judge upon what grounds he sought a decree of separation, the applicant replied that his wife was driving him crazy with her incessant stream of talk; that she talked so much at night he could not sleep. The judge then asked what she talked about, and the answer was, "She doesn't say." Often this reply seems to be a not inapt description of some profound exposition of Einstein's revolutionizing conception of relativity.

In view of the highly formidable character of the task, namely, that of providing a popular presentation of Einstein, I hesitate to venture a lance where so many others have apparently been broken. However, it must be done. I could no more escape it than I could foil the operation of the Law of Gravitation or the new geometry of space-time, the two historic attempts to account for the "apple's fall" and the facts of planetary motion. So completely interwoven with this universe of space and time has this new view become that no person can afford to be without knowledge of it. True, it is utterly opposed to common sense, but common sense has suffered so many assaults upon its integrity in the last four hundred years that its respectability is at an exceedingly low ebb. Common sense, with much rigor and vigor, holds to the eternal verities of existence, to the absolute nature of any situation, completely independent of every other consideration—utterly oblivious to the fact that its particular impression is a purely local affair, in other words, wholly relative to its own chance point of observation. That is, as far as human beings are able to ascertain, there is little of absoluteness back of natural phenomena. These apparently rock-ribbed realities of the universe are wholly relative to the observer. Two observers of the same event may arrive at totally different judgments of what has happened, and both be right. That is the meaning of relativity. And let us say also that the term *absolute* means that an event, or a natural phenomenon, shall be the same for all observers, whatever may be their locations or their relative motions. The idea that back of an event lies some intrinsic reality, existing independently of all observation, may be true, but if so, it is entirely masked; we can never know it. This wide-spread misconception is a fiction of the imagination. As we shall see, there are only two facts in this phenomenal universe that may be designated as absolute, true for all observers.

It must long since have been apparent to the reader of the foregoing chapters that the theory of relativity occupies a large place in modern physics. To-day, to attempt to conceive of physics without Einstein would be on a par with the reply made by a young man, when asked whether he had read *Romeo and Juliet,* to the effect that he had read Romeo, but he had not tackled Juli-yet. Relativity has shed a flood of light upon dark passageways and has been the forerunner of new discoveries. And we may as well emphasize here as elsewhere that this most important generalization of science since Newton was largely the product of speculation. True, a certain famous experiment afforded the stimulus to the scientific adventure, but its development was wholly an intellectual feat. As the result of mental processes alone, a new conception of the universe, a unique and revolutionizing way of interpreting natural phenomena, was born. Certain predictions, made on the basis of it, have been found almost uncannily true, even by those initially hostile to the theory. That is why, much as many would have preferred, Einstein can not be side-tracked. The truth can never be ignored.

Although I shall not try to startle you with the so-called paradoxes of relativity, yet for human beings largely at rest upon this little planet, with a vast heritage of preconceived, and often rigid, notions regarding time, space and motion, many of the perfectly valid conclusions of the theory may seem such. Often, they will appear to be utterly impossible. However, could each of us play a double rôle—alternately spending a period upon the earth, then shooting through space, comet-like, with a considerable fraction of the velocity of light, making observations along the way—the facts of relativity would become as natural to our habits of thought as are the conclusions we now possess. Our instinctive opposition to them is born of unfamiliarity. We are now in the same position with respect to Einstein, scientifically and historically, as were the people in the times of Copernicus and Galileo, when told that the earth is round, rotating upon its axis and revolving about the sun. The Einstein views are no more paradoxical than were those which gave us a true picture of the solar system. In time, they will become as amenable to the inexorable dictates of common sense as is the veriest belief of the time-honored traditions to-day.

EXAMPLES OF RELATIVITY

Let us begin by showing that the principle of relativity is not new. It is as old as human experience. Possibly the readiest example is afforded by the movements of the heavenly bodies. For centuries no one doubted that the sun, moon and stars revolved about the earth. This view accounted perfectly for the facts of observation. Even today, it is immaterial, so far as appearances are concerned, whether we assume this view or accept the belief in rotation and revolution. The interpretation placed upon these phenomena is relative to one's view-point and to one's degree of knowledge. To a savage, these movements mean one thing; to a twentieth-century scientist, something quite different.

In 1901, a new star blazed forth in the constellation of Perseus. Calculations based upon reliable astronomical data indicated that the celestial catastrophe accounting for this happening had occurred three centuries before, in 1603. The uninformed earth observer upon seeing this event would assert that a new star is born "now." Were there another solar system with inhabited planets half-way between us and this new star, for those citizens of the universe, "now" would have been a century and a half earlier. And in countless centers of our own galaxy of stars, the messenger of light bearing the "news" at the rate of 186,000 miles a second is still on the way. For them, this particular "now" has not yet arrived. Thus we see that "now" is entirely a local affair. It is relative to the observer.

Every one knows how much larger the full moon looks when near the horizon than when high in the heavens. This is wholly an optical illusion. Indeed, astronomers tell us that the visual angle subtended upon the retina is actually smaller when the moon is in the former position than when it is in the latter. But we judge of the apparent size of the moon by comparison with the known size of near-by objects. When it is near the horizon, it seems to be only a little way off, and we know the sizes of the intervening objects. Instinctively, we make a mental comparison and judge accordingly. When the moon is far above the horizon, these friendly interpreters are gone, and the apparent size automatically shrinks. The little child judges the automobile on the distant boulevard to be no larger than the toy machine at his feet. He has not learned to associate size and distance. It is self-evident that these judgments are wholly relative to the view-point of the observer.

Would there be any sound, if there were no ear to catch it? Yes, and no. In the physiological sense, sound would be absent, but the physical fact of sound waves would exist just the same. So, too, of light and heat. From the earliest beginnings of terrestrial history, the atmosphere about our planet has been filled with the radio vibrations known as "static," but until yesterday there was no receiver to intercept them. Interpretations of natural phenomena are relative to a multitude of factors. To the prisoner at the bar, waiting the verdict of the jury, moments may seem an eternity, while to one rushing to catch a train, time speeds as on the wings of the morning. The sense of duration is relative to the state of the mind.

Let me repeat an oft-quoted illustration. Suppose two gunmen shoot the engineer and conductor of a long train, the former being at his post in the locomotive and the latter on the rear platform. A passenger exactly half-way between the two hears the two shots simultaneously and judges that the men were killed at the same instant. But a station master exactly half-way between the two gunmen reports that he heard the shot which killed the conductor first. At a coroner's inquest, he will, therefore, testify that the killings were not simultaneous. Who is right? Both, taking into account the particular point of view of each. After the shootings and in the interval between them and hearing the reports, the passenger on the train is traveling forward to meet the sound waves coming from the head of the train. At the same time, he is moving away from the waves coming from the opposite direction. Manifestly, the report of the shot that killed the conductor will take longer to reach him than that of the one that killed the engineer. If he hears them at the same instant, the conductor must have been killed first. The station master wins. However, it is perfectly apparent that the interpretation of these events is relative to the conditions surrounding each observer. What is simultaneity for one is not for the other. The motion of an observer alters his judgment.

Both Newton and Galileo knew that all motion is a matter of relativity—that there is no means of determining whether there is any such thing as absolute motion, or absolute rest for that matter. If we were mounted on a body, alone in empty space, with no other heavenly body in sight, it would be impossible to tell whether we were moving or at rest. We have all had the experience of sitting in a passenger car while another train on a track beside ours begins to move. At first we are actually puzzled to know whether it is our train that is in motion or the other. Silently, smoothly, without jar or vibration, we seem to experience a delightful sensation of motion. Until we can catch a glimpse of the solid earth or of some object known to be stationary, the mystery persists. Just so with absolute motion. If there is in the universe no object of reference known to be at perfect rest, there is no possibility of determining whether there is anywhere any absolute motion or not.

Suppose that our planet and a celestial "airplane" were alone in empty space and that the airplane were moving at the rate of a thousand miles a minute in a frictionless medium, the sort of a medium that the immaterial ether has always been imagined to be. From our point of view, the airplane would be in motion, while to the occupants of the airplane it would be our earth that would appear to be enjoying the luxury of spatial transition. And there would be no way of determining the matter. In each case, the motion would be wholly relative to the other object in space. Absolute motion could neither be affirmed nor denied.

A swarm of bees may be enclosed in a light-tight sphere and flying about in all sorts of directions with respect to one another, but they will have no means of knowing whether their sphere is being carried bodily through space. Let us assume that an airplane is flying at a speed of one hundred and eighty miles an hour, or two hundred and sixty-four feet per second, at an altitude of a mile. A stone is dropped by the aviator, to whom it will appear to fall in a straight line to the earth, for we recall that the inertia of the stone will cause it to move forward at the same velocity as the airplane even after it has left the hand of the aviator. To an observer on the earth, the combination of the forward horizontal motion due to the airplane and the accelerated motion of gravity will cause the path to appear to be a parabola. From the vantage point of the North Pole, the stone will seem to whirl clockwise, owing to the rotation of the earth on its axis. One of the hypothetical canal diggers on Mars will see a spiral movement about the sun. And a stellar onlooker will simply observe a motion along a curved path in the heavens. One motion is just as valid as another. In each case, the particular one described is wholly relative to the observer. In the multiplicity of reference points, all semblance of absoluteness vanishes.

As a matter of fact, this motion of the stone dropped from the airplane is subject to a multitude of influences. What appears to the aviator to be a simple, straight-line drop is really a complex and tortuous curve. While the stone is falling, its inertia, as we have noted, is carrying it forward with the same velocity as that of the airplane; the rotation of the earth gives it an additional motion at the rate of a thousand miles an hour at the equator, which may be in any one of a number of directions with reference to the inertial motion; the revolution of the earth about the sun is hurling it through space at the rate of eighteen and a half miles a second; and the apparent movement of our whole solar system toward the star Vega at an estimated rate of twelve miles a second is adding to the complexity. And whether there is anything more in all this than merely a series of relative motions, no one knows.

Again, let us imagine that we are in a railroad car with closely shuttered windows, moving along an air-line track with a perfectly uniform velocity and that our motion is entirely free from vibration. By no test whatever could we tell whether our car is in motion or not. If we were to drop a ball, it would fall to the floor in a straight line precisely the same as though we had dropped it in the depot before starting. The laws of falling bodies will be obeyed in exactly the same way in each of the two cases. You might play toss and catch with a companion, with no effect in the slightest degree from the motion of the car, however fast it might be going. If you were standing in the forward end of the car, of course the ball, as it left your hand, would partake of the motion of the train, but this would be neutralized by the advancing motion of the car, including your companion and the air it contains. However, any increase or decrease in the speed of the train or change in direction, as in going around a curve, would be immediately detected by the effect upon yourself and the objects in the car. The motion would then cease to be uniform and would become accelerated.

Examples of the fundamental principle of relativity might be multiplied without end. Chicago is west of New York, east of San Francisco, north of New Orleans and south of Winnipeg. No one would think of asking for the "true," or absolute, direction of Chicago. In each instance, we must specify the location of the inquirer or observer. The concept of up-and-down varies with our movements over the surface of the earth. The right and left of a street is relative to the direction in which we are going. There is very little in this world, the interpretation of which does not hinge upon something else. Even in the realm of thought, outside of the mathematical truths of reason, there is nothing that one can affirm as absolutely and everywhere true. And so we shall approach this subject of relativity with an open mind, with a full understanding that it is not something new and foreign to our experience, but quite the reverse.

THE MICHELSON-MORLEY EXPERIMENT

No one gets far in the discussion of relativity without being compelled to describe the famous Michelson-Morley experiment, for this was the jolt which gave the particular sympathetic vibration responsible for setting off this whole charge of speculative dynamite. Upon the picture that it revealed, Einstein founded his theory. We must review it.

We have just seen that from the standpoint of mechanics it is wholly impossible to detect absolute motion. Relative motion of one body with respect to another is all we can ever observe. However, scientists had long wondered if optical experiments, utilizing light, which was supposed to travel in the hypothetical ether, might not reveal an absolute motion through space. It looked reasonable, for presumably this universal medium, filling all space, would be at rest. In that case, a body, such as our earth, in moving through the ether would create an ether drift, or wind, as the ether streamed through its pores. The effect would be entirely analogous to the artificial breeze which one feels when he rides in an open car through still air, or stands on the deck of a moving ship. Was there any way to detect this possible fact? Maxwell suggested an experiment to this end, which was carried out in 1881 by Professor Albert A. Michelson, long of the University of Chicago and one of the most distinguished of American physicists. In 1887, Michelson, assisted by Edward W. Morley, repeated the experiment, and again in 1928 Michelson verified his now classic determination once more.

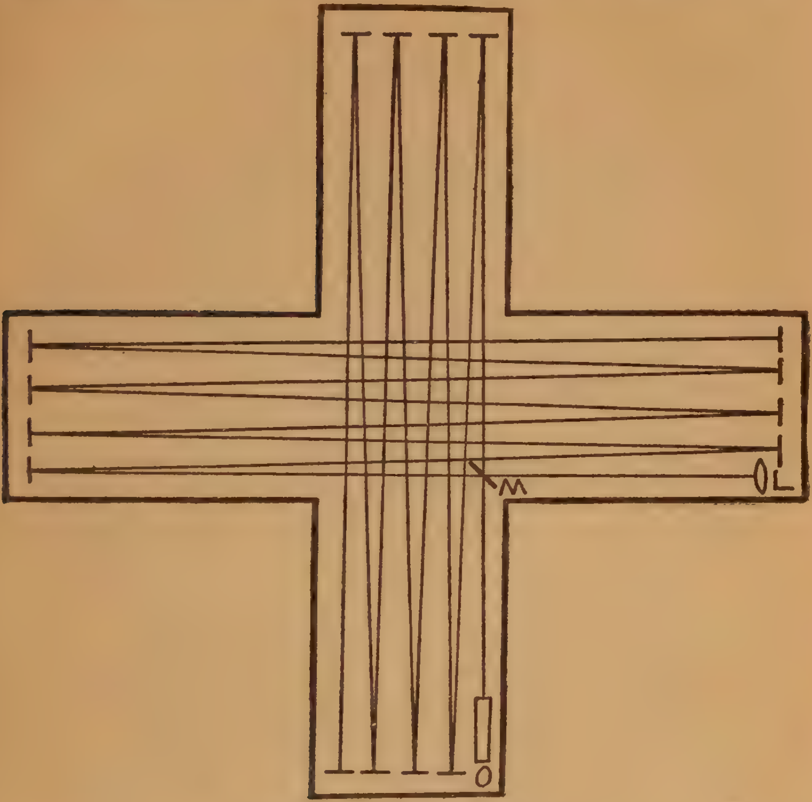
This experiment proposed to take advantage of the earth's motion through the ether. In its revolution about the sun, the earth speeds along its orbit at the rate of eighteen and one-half miles a second. Therefore, it looked perfectly plausible to assume that the existence of the above-mentioned ether drift might be proved experimentally. The ether might afford the long-sought medium of reference, the only completely stationary thing in the universe, whereby absolute motion, if there were any, could be detected. For it must be clear that, if such motion is ever to be known, something must be found which itself does not move.

Now let us look at the principle of the experiment. You can not send your voice as rapidly against the wind as you can with it, or as you can in still air. Just so with light. If there were an ether drift, a ray of light sent in the direction of the earth's motion, as it plows through this universal ocean, would be retarded. Its velocity should be eighteen and one-half miles a second less than that of a ray of light moving in empty space, free from this influence, or what is the same thing, moving at right angles to its own direction. At least, so it seemed. The illustration which fits best the particular experiment devised to test this effect is the following: Does it take longer to row a boat a mile up-stream and back or a mile across stream and back? At first thought, it may seem that the two times will be the same. However, a little calculation will show that it takes longer to make the up-stream trip than the one across. For instance, if the speed of the boat in still water is five miles an hour and the current is three miles, while it will require five-eighths of an hour in the former case, only a half-hour will be needed in the latter.

The actual experiment employed a machine of structural steel, weighing nineteen hundred pounds and floating in a trough containing eight hundred pounds of mercury. There were two arms at right angles to each other, each being fourteen feet long. At the ends of each arm, facing each other, were parallel sets of mirrors. If you were to diagram this, you would have a Greek cross, mounted with these mirrors. At one of the inner corners of this cross, another mirror, half silvered and half unsilvered, was set, such that its direction was along the diagonal joining this corner and the opposite one.

Now a ray from a calcium light, carried at the end of one of the arms, was sent to this last mirror, striking it just at the common edge of the silvered and the unsilvered portions. Consequently, half of the ray passed on to the first mirror at the opposite end of the arm on which the calcium light was mounted. Thence it was reflected back and forth between these parallel mirrors, until retracing its path it was returned to the reverse side of the diagonally-placed mirror, also silvered on one half, and from there it was reflected at right angles into a small observation telescope. The second half of the above ray was reflected at right angles to the course of the first, being sent back and forth between the sets of mirrors on the other arm a total distance equal to that traveled by its twin partner, finally being returned to the same observation telescope for examination. Thus two sets of images would be seen.

From the chapter on Newton, it will be recalled that something was said about the interference of light, a phenomenon which can be explained only on the basis of the wave theory. If the crest of one wave meets the trough of another in exactly opposite phase, a complete neutralization will occur and darkness will result. If two troughs, or two crests, meet in exactly the same phase, there will be double illumination. If the troughs and crests are partially in phase, or in step, and partially out of phase, or out of step, there will be reinforcement and interference, but to a lesser degree. Now, in each of the above cases, the ray of light was sent over the course and back upon itself. Therefore, interference must result, giving in the tele-



Michelson-Morley Apparatus

A beam of light was passed through the lens at L to the mirror M, which was half silvered and half unsilvered. From there, split in two, the separate portions pursued paths at right angles to each other, as indicated in the text, back and forth between the mirrors at either end of the arms, each being eventually returned to the small telescope at O for observation. The mirrors were so set as to produce the angles of reflection indicated. In each case, the ray hit the final mirror at a right angle, therefore being reflected back upon itself and made to retrace its path.

scope a definite set of light and dark bands, known as interference fringes. The position, width and spacing of each set will be perfectly definite. Any alteration in the speed of light along either arm would manifest itself in a shifting of these two sets of interference fringes with respect to each other.

Now this apparatus was set up in a basement laboratory of a building resting upon a planet which is rotating on its axis and revolving about the sun. Clearly, it was impossible to know which arm was directed along the path of the earth's hypothetical motion through the ether. However, if the apparatus were slowly rotated during the experiment and if the experiment were repeated at various times of day and night and at different periods of the year, the effect of this ether drift must sooner or later manifest itself in a shifting of the interference fringes. And let it be said that the apparatus was accurate enough in its construction to detect with ease a variation in the velocity of light as small as one one-hundredth of the theoretical. That is, shifts in the interference fringes very much less than what should be produced could be seen without difficulty.

Let us be perfectly clear as to what was expected would happen. Just as in the case of the boat rowed up-stream and back and across stream and back, it was supposed that the ray of light which happened to be traveling in the direction of the earth's motion through the ether would be retarded in its progress so that it would return to the observation telescope later than the ray sent on a round-trip at right angles to this direction. In any fixed position of the apparatus, no effect would be apparent. However, if in the rotation of it one arm became parallel with the direction of the earth's motion through the ether, the retardation of the velocity of light would at once manifest itself in a shift of its set of interference fringes with respect to the other set. If this did not happen at one season of the year, it should at another.

No more beautiful experiment was ever devised. Brilliant, alike in its conception and in its execution, it will remain a classic for all time. Great hopes were pinned upon it. Once again, a momentous question was to be put to Nature, but probably no one was prepared for the answer that was returned. To the amazement of every one, not the slightest shifting of the interference bands could be detected under any circumstances, and the experiment was repeated many times and at all seasons of the year. The two rays of light returned at the same instant, always, "without variableness or shadow of turning."

Before turning to the far-reaching consequences which the interpretation of this remarkable result compelled, it may be fitting to give a brief biographical note regarding the man behind the experiment. Albert Abraham Michelson was the first scientist of this country to receive a Nobel Prize, awarded in 1907 for important discoveries in light. Although an adopted son, having been born in Germany, he won an appointment to the Naval Academy at Annapolis, graduating in 1873, at the age of twenty-one. At Annapolis, Michelson acquired a fondness for science and mathematics, and two years after graduation he returned to his alma mater as instructor in chemistry. After four years in that post, he changed for one in the office of the *Nautical Almanac*. At twenty-eight, he went abroad for study, returning to take a position in the Case School of Applied Science, in Cleveland, where his famous experiment was first carried out. For a time, he was at Clark University, but since 1892 he has been head of the department of physics at Chicago University.

Michelson has made the world's most accurate determination of the velocity of light, and has done remarkable work in devising methods for the measurement of the diameters of many stars. We all remember the sensation created a few years ago by his measurements of Betelgeuse.

An incident of Michelson's career throws an interesting side-light on the character of the man. At one time, he had received an invitation to address a number of scientific societies in South America. Although he was familiar with a number of foreign languages, he did not know Spanish. However, he knew that his hearers would not be well acquainted with English. Therefore, on board the ship that carried him southward, he studied the language of his hosts, with the result that he was able to make himself understood without difficulty.

So long as the theory of relativity dominates our conception of the physical universe, the name of Michelson can not be forgotten.

AFTERMATH OF THE MICHELSON-MORLEY EXPERIMENT

It is difficult to overestimate the significance of the experiment just described. Already, you can see its consequences. Let us state some of the questions which this unlooked-for result immediately raised. Does the earth have an absolute motion through space? Is there any ether? If so, does it not seem certain that it is carried along with the earth, that is, the ether in the immediate vicinity of the earth? Is not the velocity of light a constant and absolute quantity, the same for all observers under any circumstances, unaffected by every influence whatsoever? All of these questions were perfectly legitimate and were being asked by scientists everywhere. A pretty tempest had been raised. Others repeated the experiment, but with the same results.

Regarding the ether, Michelson held to the view that it is carried along with the earth. On the other hand, Sir Oliver Lodge had performed an equally exact experiment tending to show that the ether is not carried along by matter in motion. In a lecture in which he referred to this experiment, Lodge said, "I whirled steel disks at a great rate till they nearly burst, and sent light round and round between them, that way round and this way round, and compared the time taken to go round *with* the disks with the time required to go round *against* the disks; for if the ether had been carried round with the disks the beam one way would have been accelerated, and the other way retarded. There would have been a small effect. There was none. The ether was not carried round with the disks. This proved that ether and matter are mechanically independent of each other, there is no friction; matter moves without the slightest resistance, and its motion does not affect the velocity of light in its neighborhood.'' Of course, it is easy to see that if the ether were carried along with the earth, there would be no ether breeze, and the negative result of the Michelson-Morley experiment would be accounted for. But these two experiments, entirely contradictory, presented a blind alley from which there seemed to be no escape.

It may be well to take this opportunity to say that there is no experiment of any description that demands the ether for its explanation. No means of detecting its presence has ever been devised. It was confidently believed in advance that the Michelson-Morley experiment would afford the long-sought proof, but it did not. The only ground for assuming an ether is that of logical necessity. It seems unthinkable that radiant energy should travel through space without something in which to travel. How can we have waves, if there is nothing to wave, or the phenomenon of interference, if there is nothing to interfere? Can it be possible, as some have thought, that empty space takes the place of the ether? But, if we endow space with the former properties of the ether, nothing has been gained. We are in as difficult a predicament as ever. Einstein finds no need for an ether. It is immaterial to him whether there is one or not. And there the matter stands.

At least, we thought it stood there when the foregoing paragraph was written. Since then, however, Professor Dayton C. Miller, of the Case School of Applied Science, announces that he has detected an ether drift of six miles a second. His first announcement to this effect was made in 1925, and in the intervening time he has repeated the Michelson-Morley determination many times with highly refined apparatus. He feels certain of a positive, instead of a negative, result. Professor Miller maintains that what were attributed in the original determinations to slight experimental errors are really due to the earth's motion through the ether. It is too early yet to reach a final conclusion, but we may be sure that the scientific world will give every consideration to Professor Miller's claims.

Even granting that the ether drift exists and that there is such a thing as absolute motion, the theory of relativity would not be invalidated. In its fundamentals, it would still be as true as ever. Do not get the idea that you do not need to read beyond this point until the matter is settled. The theory of relativity is as firmly established as the law of gravitation. Should Professor Miller's claims prove to be entirely true, no longer could there be any doubt as to the existence of an ether. Uncertainty in this fertile field of scientific speculation would automatically vanish. That would be a distinct gain.

THE FITZGERALD-LORENTZ EXPLANATION

Probably the most ingenious avenue of escape from the dilemma created was provided by George F. Fitzgerald, of Dublin, and independently by H. A. Lorentz, of the University of Leyden. These men made the bold assumption that a moving body contracts along the line of its motion. A yard-stick, for instance, is shorter when held in the direction of the earth's motion through space than it is when laid across this direction. An individual lying in his berth in a Pullman sleeper would be slightly shorter than when standing up. The train itself would be a trifle shorter when in motion than when at rest. At any of the ordinary velocities possible to obtain here on the earth, this contraction would be negligible—too infinitesimal for measurement. However, for velocities approaching that of light, it would be large. At 161,000 miles a second, a body would shrink to half its length when at rest. At the velocity of light, the length in the direction of motion would become zero.

Manifestly, this assumption would overcome the difficulty, for the contraction was regarded as just sufficient to counteract the ether breeze. If the arm of the Michelson-Morley apparatus in the direction of the earth's motion were contracted to just the right extent, the ray of light back and forth along that path would have a slightly shorter distance to travel than would the ray along the arm at right angles. Therefore, the retardation in the velocity of light would be just neutralized. This theory made necessary a stationary ether and a bona-fide ether drift. Furthermore, the contraction could never be detected, for any measuring instrument placed along the arm in question would contract to the same degree. As has so often been said, it seemed on this basis that Nature might be in a conspiracy to defeat any attempt at such measurement.

All of which serves to illustrate that the values we assign to space and time are wholly relative. If everything in the universe were suddenly increased tenfold in size, we could never discover the fact. Our measuring-rods and our sense impressions would all correspond with the new order. Taking the Fitzgerald contraction as an illustration, suppose we were flying through space in that celestial airplane at the rate of 161,000 miles a second. When standing up at right angles to the direction of motion, our height might be six feet. If we should lie down, however, it would shrink to three. But we could not detect it. Our retina would be contracted in the same way. A yard-stick placed in the direction of motion would automatically shrink to half its original length, and still it would appear to be as long as ever. If we were to stand up, facing the direction of motion, our height would be normal, but we should be very thin. At a velocity close to that of light, we should appear as a paper wafer, and at the velocity of light our fore and aft dimension would vanish.

Fitzgerald and Lorentz put forth this theory in all seriousness, and the latter backed it up with rigid mathematics. He based his calculations on the known electrical structure of matter. He assumed that the dimensions of the electric and magnetic fields which accompany the electrons in their orbital paths about the nuclei of the atoms change with the velocity of motion. It was supposed that the force of cohesion, which holds the molecules of bodies together, is electromagnetic. Would it not also be plausible to assume that this attraction becomes slightly greater in the direction of the ether drift through a body, that is, in the direction of its motion? For electromagnetic fields exist in the ether, if there is one. Lorentz proceeded to develop a precise set of mathematical equations, based on Maxwell's electromagnetic theory of light, which would just account, on this hypothesis, for the observed results of the Michelson-Morley experiment. They are technically known as the "Lorentz Transformations."

Now there has been a deal of misunderstanding regarding this much discussed solution of a difficult problem. Often the reader is left in doubt as to whether the author wishes him to understand that this "contraction" is a real physical contraction or a fictitious one. Let it be said, then, that, while the originators of this hypothesis did believe in the reality of this alleged effect, as well as did many other eminent scientists for a time, no one believes in it to-day. As we shall see, however, a remarkable parallelism exists between this hypothesis and one of the most important features of Einstein's theory of relativity.

Lorentz, who died at his home in the Dutch town of Haarlem in 1928, was one of the most eminent physicists of the new era. A colleague, Dr. Alfred Zimmern, in a letter to an American friend, wrote regarding his passing as follows: "The funeral was one of the most moving occasions in which I have ever taken part. The whole of Holland seemed to be in mourning and when the procession passed through the town of Haarlem from one end to another the whole population seemed to be in the streets. The ceremony itself was very simple, one speaker in Dutch, followed by Rutherford, Langevin and Einstein, and next day Einstein gave a lecture on his work at the University of Leyden, which was closed on the day of the funeral. I never had such a strong sense of the power of science as an international force or what a perfect union between intellect and character can achieve in commanding respect and affection.''

We recall that this distinguished Dutch physicist provided the explanation of the Zeeman effect, a discovery which was made by one of his former pupils. For this, he was awarded, jointly with Zeeman, the Nobel Prize in physics for 1902.

Assuming for the moment that the Fitzgerald contraction were a physical fact, the ether would be saved, and the possibility of absolute motion would still haunt us, although we should be as little able to detect it as before. Furthermore, this condition would have turned our estimates of the dimensions of heavenly bodies, in cases of any considerable velocity, into a state of perpetual flux. However, at relatively small velocities, the contraction was not large. An idea of its magnitude may be had from the fact that the diameter of the earth in the direction of its motion would be shortened two and a half inches.

The ghost of this bizarre hypothesis now having been fully laid, we may turn to a consideration of the real subject of relativity.

THE COMING OF EINSTEIN

Eighteen years had passed since Michelson's second failure to detect the ether drift, when in 1905 Einstein came upon the scene with his Special Theory of Relativity, to be followed ten years later by his General Theory and in 1929 with a still further generalization. Not until Einstein turned the search-light of a new and revolutionizing conception upon this knotty problem did any one realize the full significance of the Michelson-Morley experiment or catch a glimpse of the path leading to the solution.

In Einstein's Special Theory of Relativity, we find two principles: all motion is relative, there being no possibility of detecting absolute motion; and the velocity of light is an absolute quantity, the same for all observers, and independent of the motion of the source of the light.

In this first enunciation of his theory, Einstein dealt only with uniform motion in a straight line. He did not at that time consider the effects of accelerated motion, such as that due to gravitation. That phase of the matter did not come until the statement of his General Theory in 1915.

Now let us examine each of these principles and see what are some of the consequences to which they lead. For an observer moving with a perfectly uniform straight-ahead motion, all physical laws hold. No experiment or process, whether in the realm of mechanics or in that of electromagnetism would be affected in the slightest degree by such motion. For this reason, no one from Newton to the present has ever suggested that it would be possible by any experiment based on mechanics to determine the question as to the reality of absolute motion. Taking account of the failure of the Michelson-Morley experiment, Einstein concluded that by no physical test whatever, be it mechanical or electromagnetic, could more than relative motion be detected. And again, if two bodies, or systems, are at rest with respect to each other, or what is the same thing moving with uniform velocity, each at the same rate of speed, any physical measurements made by an observer on one system would hold perfectly for an observer on the other system. For instance, could an observer on one such system measure the height of a mountain on the other system, his result would correspond precisely with the measurement made by the observer on that system. That, in substance, is the meaning of the first principle, and surely there is nothing startling about it in any way. It is only when coupled with the second principle that the real consequences of the theory of relativity appear.

The real significance of the second principle lies in the fact that the velocity of light is one of the two absolute quantities in the universe. That is, it is the same for all observers under any and all circumstances. Nothing can go faster than light, and every observer, no matter how he may be moving, whether toward a ray of light or away from it, will obtain the same velocity for light, provided his measurements are accurately made. It makes no difference whether the source of light is moving or standing still, or with what velocity or in what direction with respect to an observer, the velocity of the light it sends out will always be precisely the same. That is, the source of light is always at the center of the waves it sends out, regardless of its motion.

Now let us look at some of the logical deductions from this state of affairs.

A few simple illustrations will help to make clear the implications involved in this conception of the velocity of light. We shall here only state these situations and let the task of explaining them follow later. We all know that an echo is the result of reflected sound waves, and the velocity of the reflected waves is identical with that of the direct waves. Now sound travels about eleven hundred feet a second. Suppose we have a train whose length is twice that distance and which makes a speed of sixty miles an hour, eighty-eight feet per second. On the engine, we have erected a screen for the reflection of sound waves. When the train is standing still, the echo from a shot fired from the rear platform will come back in four seconds, assuming that the length of the train is just twice the velocity of sound at the time. If, however, the train is moving at the above-mentioned rate, while the sound waves are traveling forward the screen will be moving away from them. On their return, following reflection, the listener on the rear platform will be traveling forward to meet them. This is a case quite similar to that of the boat which was rowed up-stream and back and across stream and back. Calculation will show that it takes a little more than four seconds for the return of the echo when the train is moving. But, if sound traveled with the velocity of light, the echo would return in four seconds, whether the train were standing still or moving, and the velocity of the train would have no effect on the result whatever. Absurd, opposed to common sense, yet true.

Again, let us suppose that a train is moving down a straight track at the rate of one hundred feet per second, and that from a point a little way behind it and slightly to one side a rifle bullet is fired at the rate of three thousand feet a second. The bullet would quickly overtake the train and pass by an observer sitting in it at the rate of twenty-nine hundred feet a second. However, Einstein's dictum regarding the velocity of light compels us to believe that, if it had been a ray of light instead of a bullet which was sent after the train, the velocity with which it passed the observer would have been wholly uninfluenced by his motion. That is, it would have passed him at its normal velocity of 186,000 miles a second.

Let us put this illustration in another way. We shall imagine that we have a long speedway boulevard with cars traveling upon it in both directions at all sorts of speeds. A flash of light is also sent down the speedway. It will pass all of them at the same rate of speed, regardless of whether they are coming to meet it or going away from it. Or, let us think of a central point from which motor highways radiate in all directions. At a given instant, light is sent out from this center as a source, which will of course travel with equal velocity in all directions. At precisely this same instant, motor-cars begin traveling with varying speeds along these highways. We shall assume, too, that a passenger in each car carries a perfectly accurate timepiece. Now at the end of any given number of seconds, as determined by the timepiece of each car, the front of the light wave will be at precisely the same distance in advance of all of them. It will also be at the same distance from the central starting-point at the end of this same number of seconds.

Now I have given you a clue. The only way in which we can explain such performances is to assume that the time-keeping properties of watches and clocks are affected by their motion, and that the magnitude of the deviation depends upon the rate of motion. What is a second for one will not be the same lapse of time for another. Just what this effect is, we shall see a little later. This accounts for these remarkable results in part. Let us have other illustrations, however.

Suppose we have two celestial airplanes moving through space in opposite directions, each with a velocity equal to half that of light. Now let a ray of light pass these two airplanes, and we shall imagine that the occupants of each are equipped with instruments of scientific precision for measuring with great exactness the velocity of this passing ray. One airplane will be going forward to meet the ray, while the other will be traveling away from it. Offhand, judging by our observations of ordinary velocities here on the earth, we should say that this ray of light would pass one airplane at the rate of 279,000 miles a second and the other at the rate of 93,000. However, it will pass both of them at the same rate, 186,000 miles a second, just the same as though they had both been at rest. This seems like a hard saying, but it is the inevitable conclusion to which the Michelson-Morley experiment leads. When this experiment is performed at one time of the year, the earth's motion is in one direction; six months later it is in the opposite direction. Still, this made no difference with the results. We must remember, too, that Einstein asserts that the velocity of light is the highest velocity possible to obtain. Were one of those airplanes to obtain a relative velocity with respect to light of 279,000 miles a second, we should have exceeded this limiting value, and no velocity, relative or otherwise, can do this.

Before me lies a mathematical formula for determining the resultant velocity of light in all such cases as we have just been considering. If it were not so formidable in its appearance, I would give it to you. However, whatever values you may substitute in it and whatever conditions you may assume, the velocity of light remains in every instance the same invariable quantity. For instance, with the airplanes just considered, the velocity for light in passing each comes out 186,000 miles. In a sense, the velocity of light partakes of the nature of infinity. Of course, it is a finite quantity, but it is a limiting quantity. Just as we can not increase infinity by adding a finite quantity to it, neither can we exceed the velocity of light.

Another phase of the consequences flowing from the unique significance of the velocity of light will help us to understand something of the apparent mystery associated with the foregoing conundrums. And it is in this that the appropriateness of the term relativity appears.

FROM ANOTHER ANGLE

We said a little way back that the ghost of the Fitzgerald contraction had been laid. This is true and not true. As far as being an actual physical reality is concerned, this contention has disappeared. But as a relative effect of observation, it is still with us. Indeed, it is one of the cornerstones of Einstein's theory of relativity. And the remarkable feature of it is that the mathematical equations of Lorentz for the supposed real contraction fit the apparent one precisely. One body passing an observer on another body at a uniform velocity does *appear* to be shortened in the direction of its motion by an amount exactly equal to that calculated by Lorentz. That is, there is no such thing as the true, or absolute, length of an object. It is in every instance relative to the motion of the observer. For an observer at rest with respect to a body, its length will have one value; to an observer in motion, passing by it, the length measured by this observer will be different; and to another observer passing by with a different rate of motion the length obtained will have still another value. The only reason why we assume length to be an invariable property of a body is that we have never had in our earth-bound lives any experience of relative velocities high enough to detect its changing values. If we could move through space with, say a velocity half that of light, making measurements of other bodies apparently at rest with respect to ourselves, and then return to make these measurements again when our own relative motion had ceased, we should have no difficulty in understanding that length is purely a local affair. The value obtained by one observer is just as valid and "true" as that obtained by another, and no two lengths will agree, unless they both happen to be at rest with respect to the body being measured or are moving with the same relative velocities with respect to it. This fact of the variation in the observed lengths of measuring-rods is a factor in securing the results indicated in the foregoing section.

Let us take a concrete illustration. Suppose a train a mile long is moving by us with a velocity equal to three-fifths that of light. In some way, we contrive to measure its length with scientific precision. Instead of being a mile long, it turns out to be only eight-tenths of a mile. At the same time, a passenger on the train makes the same measurement, and finds it to be a mile. We get a glimpse of his yard-stick and it appears to be only eight-tenths as long as ours. Another passenger measures the length of our station as he passes, which we believe to be two hundred feet. He makes it only one hundred and sixty feet. He, too, gets a glimpse of our yard-stick, and it appears to be contracted in length, just as his does to us. For these relativity estimates are reciprocal. As far as motion is concerned, the train might just as well be regarded as at rest and the station-house in motion. If it were not for the vibrations on the train, the accelerations due to bumps and to slight inequalities in the distance apart of the rails, there would be no means by which a passenger, without looking at the surrounding landscape, could tell whether the train or the station were the moving body.

Again, you look at the dinner plates on the tables in the diner. Although perfectly round to the passengers sitting at the tables, they appear oval to you. The dimension in the direction of their motion has apparently contracted to four-fifths its value to an observer at rest. But dimensions in the crosswise direction are unaffected. A passenger standing between two of the coaches facing in the direction of motion appears thin. If he turns into a position at right angles to the former, the breadth across his shoulders narrows. If you could see him change from a standing to a reclining position, his length would automatically shorten by a fifth. And, if the passenger could make similar observations of people and objects at "rest" outside the train, he would see precisely the same effects.

Another effect is also exceedingly noticeable. These people on the train are awfully slow. It takes them one and a fourth times as long to go through the ordinary motions of life as it does us. Their gait in walking is correspondingly slow. We time them with our watches, and find this to be true. They do the same thing and make the same judgments regarding us. We appear to be just as slow to them.

Let us pause to say that this is not all nonsense. It is only the exact truth as to the way things would appear, if we could make that sort of observations. The whole story can be plotted on paper to show that this would be the case. The mathematical formula governing the calculation of observed lengths under any conditions of relative motion is easily derived. The factor for making these adjustments is found by taking the square root of one minus the square of the relative velocity divided by the square of the velocity of light. That sounds barbarous, I know, but it does not look so bad expressed in symbols.

We will put a new twist into the picture of this relativity train by assuming that it meets another on a parallel track, moving with a velocity of one-fifth that of light. This will make the relative velocities of the two with respect to each other four-fifths that of light. It will necessitate, too, a whole new set of measurements of length and time between the two trains, as compared with those relating to the first train and the stationary observer. Thus, the length of the first train, as measured from the second, will be still shorter than that obtained by the observer in the station. The movements of the passengers on the two trains, as observed by each other, will be slower even than they appeared to be to the stationary observer when viewing events on the first train. And should a passenger on the second train and the man in the station observe some particular event on the first train, say a signal given by the conductor to the engineer, they would each place it at a different time, although the light rays bearing the message would pass each of them at the same speed. In other words, "now" is a relative term. It does not mean the same for two observers having different relative velocities with respect to a third.

However, if we were to consider two trains, each having the same relative velocity with respect to a third, the measurements, both of times and lengths, which the observers on these trains would make of events on the third would agree precisely. The conclusions, too, which the observers on one of these trains would make regarding events on the other would agree with those of the passengers on that train, for the trains would be relatively at rest with respect to each other.

Now, while these contractions in length are not actual physical changes and would be wholly undetected, in fact would not exist, for one traveling with the moving body, they are none the less real. For any relative velocities obtainable here on the earth, they are unmeasureable. Were a train one thousand feet long as measured by a passenger to pass a second observer at the rate of a mile a minute, the apparent contraction in length would be only four hundred-millionth of a foot.

As to time, of which we shall say more shortly, two observers, having ideally accurate timepieces and traveling at different relative velocities with respect to a third system, will judge quite differently of the time which has elapsed between two events on this third system, and both will be right. Of course, the relative velocities must be of considerable magnitude to make these differences apparent. Nevertheless, they exist in the appropriate degree, whatever the velocities. Space and time measurements are wholly relative to the movements of the observers. This gives us a clue as to why a ray of light will pass all observers at the same speed, regardless of how each may be moving.

Eddington has given an interesting illustration of these effects in his *Space, Time and Gravitation.* He says: "There is a remarkable reciprocity about the effects of motion on length, which can best be illustrated by another example. Suppose that by development in the powers of aviation, a man flies past us at the rate of 161,000 miles a second. We shall suppose that he is in a comfortable travelling conveyance in which he can move about, and act normally and that his length is in the direction of the flight. If we could catch an instantaneous glimpse as he passed, we should see a figure about three feet high, but with the breadth and girth of a normal human being. And the strange thing is that he would be sublimely unconscious of his own undignified appearance. . . . But when he looks down on us, he sees a strange race of men who have apparently gone through some flattening-out process; one man looks barely 10 inches across the shoulders, another standing at right angles is almost 'length and breadth, without thickness.' As they turn about they change appearance like the figures seen in the old-fashioned convex-mirrors. If the reader has watched a cricket-match through a pair of prismatic binoculars, he will have seen this effect exactly. . . . Which is right? Are we, or the aviator? Or are both the victims of illusion? It is not illusion in the ordinary sense, because the impressions of both would be confirmed by every physical test or scientific calculation suggested. No one knows which is right. No one will ever know, because we can never find out which, if either, is truly at rest in the ether. . . . It is not only in space but in time that these strange variations occur. If we observed the aviator carefully we should infer that he was unusually slow in his movements; and events in the conveyance moving with him would be similarly retarded—as though time had forgotten to go on. His cigar lasts twice as long as one of ours. . . . But here again reciprocity comes in, because in the aviator's opinion it is we who are travelling 161,000 miles a second past him; and when he has made all allowances, he finds that it is we who are sluggish. Our cigar lasts twice as long as his."*

THE MATTER OF TIME

The relativity of time is a much more fundamental matter than that of lengths. Suppose we illustrate this with another example from Eddington. Again he says: "It is a favorite device for bringing home the vast distances of the stars to imagine a voyage through space with the velocity of light. The youthful adventurer steps on to his magic carpet loaded with provisions for a century. He reaches his journey's end, say Arcturus, a decrepit centenarian. This is wrong. It is quite true that the journey would last something like a hundred years by terrestrial chronology; but the adventurer would arrive at his destination no more aged than when he started, and he would not have had time to think of eating. So long as he travels with the speed of light he has immortality and eternal youth. If in some way his motion were reversed so that he returned to the earth again, he would find that centuries had elapsed here, whilst he himself did not feel a day older—for the voyage had lasted only an instant."†

Of course, this all seems incredible, like a tale from fairyland, and yet it is the sober truth as deduced by exact scientific analysis. Before we proceed to show why it must be so, suppose we take one or two other examples. One imaginative enthusiast of relativity has pictured a scientist as faring forth into space in some sort of a conveyance capable of traveling at a speed slightly less than that of light. In this case, time would not entirely stand still. He carries with

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*Reprinted by permission of the publishers, The Macmillan Company, from *Space, Time and Gravitation*, by A. S. Eddington.

†Ibid.

him instruments for observation and measurement of distances and accurate clocks for keeping the time. In his log book, he keeps a faithful record of each day's events. Busy with his work, he almost forgets the passing of time until one day he discovers that according to his records he has been absent five years. Immediately, he reverses his course and returns to earth. When he left, the papers in all cities carried big head-lines telling of his great adventure. He has been absent ten years by his reckoning and anticipates a royal welcome upon his return. Imagine his dismay at finding that no one remembers him or his exploit at all. He creates no sensation whatever. Upon inquiry, he discovers that he has been gone, not ten years, but a hundred. Industry, modes of living, manners and customs have been totally revolutionized. He is in a new world, in the midst of strange peoples, and yet actually only ten years older than when he departed. He has Rip Van Winkle beat five times, and besides the foregoing is only what would really happen, provided the specified conditions could be realized.

Let us imagine twins, each twenty years old. One remains on the earth while the other cruises through space with the velocity of light for fifty years. For this inhabitant of the celestial spaces, time does not pass; physiological processes are at a standstill; he does not age. At the end of his fifty years, he returns to earth to find his twin brother an old man of seventy years, but he himself is not a day older than when he left. In spirit, bodily vigor and appearance, he is still only twenty years old.

No practitioner of the time-honored art of magic ever laid claim to ability to perform such feats as these. This even puts in the shade Ponce de Leon's fountain of perpetual youth, for that Spanish adventurer did concede the fact of old age. How does it come about? Have we been merely indulging in "make-believe" stories, or is this the bona-fide gospel of relativity? Indeed, the latter is true. It turns out once more that truth is stranger than fiction. Let us have the explanation.

At several places in the foregoing chapters, we have referred to the discovery, first predicted by Einstein on the basis of his theory of relativity, that the mass of a body, that is, its inertia, increases with velocity, reaching infinity at the velocity of light. Incidentally, this is one of the reasons for declaring that this is the greatest velocity possible to obtain, for it is inconceivable that the mass of a body could exceed infinity. In fact, the velocity could never quite reach this value, although high-speed electrons travel nearly that fast. Now, as we have seen, precise, scientific measurements of the mass of rapidly moving electrons confirm this prediction of Einstein's. Mass does increase with velocity just as his theory indicates that it should. We might say that the means of measuring this increasing mass is by the deflections of these particles in a magnetic field of known strength. From the paths of the deflected particles, the mass can be determined.

Let us see what bearing this increasing mass has upon the time-keeping qualities of a watch. If the inertia of the watch movement increases, the energy pent up in the coiled spring will not be able to drive the mechanism with the same speed that it did when the watch was at rest. The hands will travel more slowly. Time will not seem to pass as rapidly. At a velocity of 161,000 miles a second, the "wheels" will turn only half as fast. While a watch on the earth will register twenty-four hours, this watch will indicate only twelve. If a watch could be projected through space at the velocity of light, its mass having reached infinity, the hands would not turn at all.

So also with physiological processes. This increase of mass would make one more sluggish. A celestial traveler at high speed would live more slowly. The heart would not beat as rapidly. The rate of muscular activity would be slowed down. The cycle of digestion and fatigue would be decreased proportionately. The activity of the brain cells, the thoughts and the emotions would all come under the same spell. In short, the process of aging would be checked.

One would travel from youth toward old age at a slower speed. At the speed of light, all bodily functions would cease. One would not age at all, and yet he would not die. He, literally and figuratively, would be in a state of suspended animation. He would be, as the Infinite is often pictured, in the presence of an eternal now.

We can now understand why each observer will always make the velocity of light the same, regardless of whether he is at rest or in motion and no matter what his speed may be or in what direction he may be traveling. The velocity as he measures it from his system will always be the same. In the first place, whatever the speed of the observer, his estimates of time are affected. Then, too, his judgments of space distances are altered. And in every instance, the compensation is complete. It is inherent in the fundamental workings of Nature. The relativity of space measurements and of time judgments strikes a perfect balance. It will not be necessary here to go into detail regarding any of the concrete illustrations cited earlier in this chapter. We have indicated the underlying principles of relativity whereby the unraveling of the mystery is effected.

More than ever it becomes clear that in the realms of relativity the idea of time as an absolute and invariable quantity vanishes. A period of a year means one thing for a person on the earth and quite another measure of duration for one traveling with any considerable fraction of the velocity of light. The fact that we can not personally attain to these velocities does not in the slightest alter the theory. It is just as valid for all that. However, not until Einstein revealed the truth did we realize that we live in a universe in which relativity holds sway.

We have now outlined in substance Einstein's Special Theory of Relativity. As the reader has discovered, it has to do only with the relativity judgments of time and space in cases of systems moving with uniform motion with respect to one another. However, such a view does not picture the universe as it is, for only in ideal instances is motion uniform and in a straight line. Motion is usually irregular and accelerated. Therefore, it became necessary for Einstein to extend his theory to include both uniform and accelerated motion, thereby covering the subject of gravitation. This, he did in 1915, and to a consideration of his General Theory, I now invite your attention.

THE GENERAL THEORY OF RELATIVITY

Possibly, we can do no better in beginning this section than to remind the reader that a space of three dimensions only is now obsolete. In 1908, Minkowski at a scientific gathering in Cologne, Germany, boldly proclaimed that "henceforth space by itself and time by itself shall sink to mere shadows, and only a union of the two shall preserve reality." Thus, for the first time a formal declaration of independence from the Newtonian ideas of space and time was made. This advanced thinker and some others were beginning to see that time and space are intimately associated. One can not exist without the other. Time becomes a fourth dimension. The three traditional dimensions of space are those along which we must make an effort to move ourselves. Time is the inescapable dimension, or direction, in which we move without exertion. We move in time and we exist in space. The two are no more separable than are right and left, or up and down. Einstein made this principle a corner-stone of his General Theory. Let us examine it further.

Space and time are ideas, not realities. The thing that we sense is matter, not space. From this perception of matter, we infer a universal emptiness, which we call space. But had we no knowledge of matter, the idea of space would never cross our minds. Likewise, of time. We perceive the sequence of events. We see one event following another, and we invent the abstraction, called time, in which we think things happen. But we do not see time any more than we see space. We see matter and we witness events.

Space and time themselves, however indispensable in a practical world, are products of the imagination. If there were nothing to put in it, we should have no need of space, and if nothing ever happened, there would be no time. We have seen that space and time measurements are wholly relative. Neither are there back of these mental creations any absolute entities, fundamental in the structure of the universe, each existing in its own right independently of the other.

When you stop to think of it, can you imagine the existence of an object in space without its also existing in time? And can you conceive of the occurrence of any event which is not related to both time and space? Suppose we think of space as mere emptiness, a place to put things, can we separate this creation from the time element? If you leave your home for a travel trip and then return, have not both you and the home in the interval moved along this fourth dimension of time? Time has been an inescapable factor of every space relation. Even the measurement of time is spatial, for it employs a mechanism which occupies space. If we wish to locate an event, say an accident, we must have both space and time elements. Let us assume that it is an elevator accident on the tenth floor of the Times Building at the corner of Broadway and Seventh Avenue, New York City. These specifications give the location in a three-dimensional space, but we also need to know the time of the accident. Every moment of your life you are existing both in time and in space, and the path which you follow through this space-time continuum is called your "world-line." That world-line details your complete life history. The events which transpire along its course are the incidents of your career. Where your world-line crosses another, as for instance when your car and an express train reach the crossroads at the same time, you sometimes come to grief. What a splendid thing it would be if we could occasionally dodge this fourth dimension of time. But time and space are inextricably related. Out of them are woven the fabric of past and future. Sullivan, in *The Bases of Modern Science*, says, "The future must be supposed to 'exist' as indubitably as the past. Events do not happen; we come across them."

I hope no one is tangling the gray matter of his brain into hard bow-knots in the attempt to picture this complex union of time and space. It can not be done. While we have experience of events which occur in time and space and it is only by impressions of distances and times that we can become aware of our physical existence, we can have no concrete mental conception of the nature of the combination. We can see perfectly that the perceptions of time or space can not be experienced independently of each other; that the two are knit together by an indissoluble bond of kinship; but a picture of the relationship is as impossible as would be that of an electromagnetic wave. And there should be nothing out of the ordinary about this. We do not try to visualize the ideas of energy, electricity or cosmic rays. No more should we the continuum of time and space. It is the medium through which ceaselessly wend the myriad tracks of world-lines, and where these lines intersect occur the physical events of the universe.

Now there is one other characteristic of space-time which we must get. We call it the "interval" between two events. It is one of the two absolute quantities of this physical universe. That is, the interval separating two events is the same for all observers, just as the velocity of light by whomsoever measured and under whatever conditions never varies. Two observers in measuring the "distance" between two events may split the time and space elements up differently, but the interval in space-time will always and everywhere be the same. It contains the factors of both space and time and, therefore, is unpicturable. In measuring it, the simple three-dimensional space of Euclid's geometry no longer holds. It may surprise some of us to know that there are other geometries than that of the Greek master who provided the basis for the axioms and theorems which frequently disturbed our schooldays. Those axioms are no longer regarded as absolute necessities of thought. For instance, in the universe of Einstein parallel lines may meet. And it is in such a universe of non-Euclidian geometry that the interval between two events must be measured. For that reason, the concrete meaning of this quantity can not be made clear. Nevertheless, it is entirely susceptible of measurement in the mathematics of Einstein. Like most other things in this world, we must accept this fact on faith.

An illustration may be helpful. We might assume that the "straight-line" distance between New York and Liverpool would be the shortest distance. Or we might sail due east a certain distance and then north. However, the most direct route will be along the arc of a Great Circle. Such a route is called a geodesic, whether it is measured over the surface of the earth or between two events in the space-time universe in which the stream of history takes its course. The Euclidean straight-line, except far from large masses of matter, is not the shortest distance between two events in space-time. That is, it is not a geodesic, the sort of a route which measures the interval between two events. And an event, lest we forget it, may be defined as a "point" in space-time, something which occurs at a specified moment and at a specified place. The world-lines connecting events are geodesics. Light travels along geodesics. So do the planets and all bodies moving under the influence of gravitation.

Now, since judgments of time and space are wholly relative to the motions of the observers, the components of time and space determining the interval between two events may vary, but the interval itself, the result of combining any such set of measurements, will be the same for all observers. That is, it is an absolute quantity. And let us bear in mind that no one can ever make a pure space measurement without also making a time measurement. All that we can do is to measure the distance from a particular point of space at a particular moment of time to another point of space at another moment of time. Thus, the interval between two events is a complex of time and space. The interval from birth to death is a long, and often devious, path through a small portion of this universe of space and time.

Probably the most difficult portion of Einstein's General Theory to understand is his conception of curved space. Absurd, unthinkable, utterly opposed to common sense, the child of a "disordered" brain—all this is granted, and yet the warping of space in the vicinity of a large mass of matter, like our earth or the sun, may account for the "apple's fall" or the path of a sunbeam from star to earth. It was just so when people were told that the surface of the earth is curved and not flat. That we can not imagine how curved space would look does not weaken the argument for its existence. And it is not curved space of three dimensions which Einstein means, but the combination of time and space in which events occur. In its distorted form, curved and folded by a large mass of matter, it does not conform to the three-dimensional space of Euclid's geometry. But this is not the first time that this geometry has had to be abandoned in the practical application of space measurements. On the surface of a sphere, we can not draw a square, and there the laws of the triangle do not hold. If one were to travel a certain number of miles north, and the same number each east, south and west, one would not return to one's starting-point, for one is not moving over a flat plane surface, but over a curved surface. Likewise, when we describe a circle on the surface of a sphere, the relation of circumference to diameter, measured on the surface of the sphere, is not the same as it is in the case of a circle described on a plane surface. Now the curvature of space holds the same relation to three dimensions that the geometry of a spherical surface holds to that of a plane surface. One who had been accustomed only to flat plane surfaces would have the same difficulty in understanding the properties of spherical surfaces that we do in interpreting the curvature of space. But inability to understand is no ground for rejection.

This idea of curved space led to a new and revolutionary conception of gravitation. And mind you, the possibility of curved space is not a fiction of the imagination. The mathematics of it had been worked out long before the time of Einstein. Einstein simply adapted this intellectual "monstrosity" to meet the requirements of a gravitational field which should eliminate the necessity for assuming a force of gravity. Let us see how he did it.

EINSTEIN AND GRAVITATION

If one should find that a marble placed near the outside of a room always rolled to the center of the floor, one might assume one of two things: either there is some mysterious force attracting the marble, or the floor is curved. So it was with Newton and Einstein. Both saw the planets pursuing certain definite courses and bodies falling through space to the surface of the earth. One assumed a force to account for these phenomena; the other attributed them to curved space. And, as we think of it, why should we assume a force in the presence of inert matter? Despite the fact that it bristles with centuries of traditional significance, the idea of force is largely an invention to cover up our ignorance. The idea of curved space is not nearly so baffling and mysterious as is that of force. We are simply more familiar with the latter. That is all. If we could have a group of pupils who had never been exposed to the notion of force, there would be no difficulty in teaching them the newer view of gravitation. Some time the present picture may become as obsolete as is that of the Ptolemaic astronomy.

It may be that the orbit of a planet or the track of a falling body is simply the path of least resistance through a time-space which has been warped and distorted by the presence of a huge gravitational body. A river follows the valleys in its course to the sea because the topography of the landscape requires such a course. Who knows but that the topography of space may determine the routes of bodies through it? In the depths of space, far from the influence of gravitational masses, the inertia of a body, just as Newton supposed, will compel motion in a Euclidean straight line, but near to the heavenly bodies the geodesics of time-space are curved. This is not due to any attracting force, but to the crumpled condition of space in those parts of the universe. An aviator, high in the heavens, may see a landsman following a very devious route to a neighboring city. He wonders why, not knowing that the rugged surface of the earth compels it. Just so, the physical conditions of space and time may erect celestial highways of least resistance. At least, so it seemed to Einstein.

Did you ever view the landscape in the distance through the expanding layers of heated air rising from the surface of a hot field? Or look across a hot stove or radiator to the objects beyond? If so, and we all have, you are familiar with the wavy moving appearance which things present. This is because the density of the expanding air is constantly changing, causing a corresponding change in the direction of the rays of light coming to us through the air. We might say that the air has been distorted, and the analogy may help us to understand the possibility of curved space in the vicinity of matter.

The story is told that Einstein received the stimulus for the development of his theory of gravitation from seeing a man fall from the scaffolding of a building in Berlin and strike upon a heap of soft rubbish. Rushing from his room, he asked the man what sensations he had experienced, and received the reply that he had felt no downward pull, as though a force were acting upon him, at all. This set Einstein to wondering about the reality of the traditional force of gravitation and whether or not he might be able to extend his theory of relativity to include accelerated motion as well as that of uniform motion.

Einstein, too, tells us of another circumstance which set him to thinking along similar lines. He imagined a huge rotating disk, carrying an observer and a large dome, so that the observer could not tell by looking at outside objects whether the disk were in motion or not. That is, the dome was to rotate with the disk. He supposed the disk at first to be at rest, so that, as the observer walked about upon it, he would experience no difference in his sensations in one part of the disk from what he would in another. However, if the disk were set in motion, he would apparently feel a "force" impelling him outward, and the farther he moved from the center the greater this force would become. If he were ignorant of the situation, he might assume a force driving him outward from the center, or one attracting him from the circumference. This effect, we say, is due to centrifugal force, but as a matter of fact it is the result of inertia. It is simply the tendency of the man's body to continue in straight-line motion, tangent to the curve in which he is moving. There is no force of any sort acting upon him. It is simply this ages-old property of inertia, or inactivity. He can not help himself. Granted the circular motion, the path of least resistance is in the direction that his body wants to go.

Now, there is a remarkable similarity between this effect and gravitation. It does not matter of what material the body may be composed, the action is always the same. Its magnitude depends simply upon the mass of the body. Nothing can screen it off. Furthermore, it has long been known that the mass of a body as determined by its inertia, that is, measured by the force necessary to give it a certain acceleration, is indistinguishable from the gravitational mass, or that determined by gravity. The two are strictly proportional and are measured in the same units. Artificially, as in the above illustration, we may create a gravitational field, and yet we know that the effects are all due to inertia. May it not also be true that the so-called force of gravity is just as fictitious as is centrifugal force? Why assume a force to pull a body to the earth or keep a planet in its orbit? Why is it not just as reasonable to suppose that these bodies move in these paths because of their inertia? These are the lines of least resistance through a time-space which has been influenced by a large mass of matter. Thus reasoned Einstein.

There is another way, too, of showing that gravitation, as an actual force of attraction between particles of matter, may be imaginary. We have all experienced the sense of increased weight, as an elevator starts up with increasing velocity, that is, accelerated motion, precisely the sort of motion that gravitation gives. Until the motion becomes uniform, we actually do press upon the floor of the elevator with more than our normal weight. When the express elevator at the top of the skyscraper starts downward with accelerated motion, we have a queer sensation at the pit of the stomach and a feeling as though the foundations of the earth were falling from beneath us. As the velocity becomes uniform, these feelings disappear. During this period, however, we press upon the floor with less than our weight when at rest. If all resistance to the elevator should be removed and it should fall freely, we should exert no pressure upon the floor at all. Neither, according to the testimony of the man Einstein questioned, should we have any sense of a force of gravitation pulling us downward. Bodies would have no weight. For instance, were a heavy body suspended from a spring balance attached to a hook in the ceiling, the balance would register no weight. A lever balance might be in equilibrium with unequal weights in the two scale pans. A ball released from your hand would not fall. Your hat would not press down upon your head. The customary reactions to what we call the force of gravity would all be absent. The conditions would be exactly the same as those prevailing in a box in which you might be sitting in empty space, far removed from the influence of any heavenly body.

Now imagine an observer to be enclosed in a box suspended high over one of our western prairies. All the effects of gravity will, of course, be apparent. The observer will have his customary weight; a ball dropped from any point will fall with accelerated motion; balances will behave in the usual way; all the ordinary reactions of gravity will be present. Then let this box with its occupant be transported to the interstellar depths, where neither curvature of space nor the attractive force of gravity can be present. All the gravitational effects will automatically vanish. But, magic-like, suppose this box were to begin to rise suddenly with accelerated motion identical with that of a falling body at the surface of the earth. Immediately, effects precisely similar to those of gravitation will return. The observer will press with his customary weight upon the floor; the floor will catch up with a ball released from his hand; a spring balance will pull with its usual force upon a suspended weight; in short, the observer will have no means of knowing whether these effects are the result of some mysterious force of gravity or are due to an accelerated upward motion. Here we have a capital illustration of the difference between gravitational mass and inertial mass. When the box was suspended over the prairie, a weight fell because of its gravitational mass; when it was rising with accelerated motion in the depths of space, a weight fell, not because of any gravitational attraction, but because of its inertial mass. Its inertia kept it at rest, and the floor caught up with it. The impact with which it would strike the floor would be the same in each case. Now may it not also be that all the observed effects of gravitation are simply manifestations of inertia? May not a planet follow an elliptical orbit about the sun, or an apple fall to the ground, because its inertia in either case carries it along a path of least resistance through a time-space complex which has been warped and curved in the presence of matter?

Not only did Einstein assume that this view might be true; he also proceeded to develop a new law of gravitation based upon it. Using an abstruse type of calculus, he produced a set of mathematical (differential) equations, fearful to behold, but marvelous in their ability to explain observed facts. Of this extraordinary feat, Dr. Paul Heyl says: "Theories far less formidable have fallen of their own weight, but that of Einstein has gradually compelled recognition despite its repelling appearance, solely upon performance, by reason of its ability to furnish results for it not only explained everything which the Newtonian law explained, and equally well, but it also, without forcing, explained the great puzzle of the irregularity of Mercury. Nay, more; it undertook the always precarious business of prediction, for it indicated the existence of a phenomenon hitherto unobserved, the deflection of a ray of light under the intense gravitational forces existing near the sun. This prediction has recently received the final stamp of experimental verification in the results of the 1922 eclipse expedition of the Lick Observatory. Additional weight attaches to these results from the fact that Director Campbell was known to have had no bias in Einstein's favor."*

The important point to emphasize is this: abandoning the three-dimensional, Euclidean type of space and substituting therefor a time-space complex of four dimensions, Einstein has been able to dispense with the conception of a force of gravitation. He explains, and by rigid mathematics too, all that Newton does and more. He shows that the Newtonian Law of Gravitation is but a special case of his larger and more general principle. As far as our solar system is concerned, the law of Newton deviates but slightly from that of Einstein. Still, in two important respects, Einstein's view has been proved by observation to be correct and Newton's a very little in error. Therefore, to the results of the Einstein theory, we shall now turn.

FROM THEORY TO FACT

Had it not been that the facts of observation have proved Einstein to be right, his theory, as a serious competitor with Newton's, would long since have passed into oblivion. But when a man constructs a hypothesis and then makes

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*From *The Common Sense of the Theory of Relativity*, by permission of The Williams and Wilkins Company, publishers.

startling predictions, which his brother scientists verify almost to the letter, he must be reckoned with. However absurd we regard his ideas, we can not side-track him. And Einstein has triumphed all along the line.

In the previous chapter, we have seen how Einstein's theory explained the puzzling discrepancy in the orbit of Mercury. According to Newton's law, were the sun and a single planet alone in space, the planet would describe an ellipse about the sun, returning each time to its original starting-point to begin the journey over again. According to Einstein's law, the planet would describe an ellipse as before, but it would be a slowly rotating ellipse. At each return, the planet would move forward to a point slightly in advance of its former position. Thus, in the course of time, the ellipse would come to point in a different direction in the heavens. True, this theoretical shifting of a planetary orbit was exceedingly small. In the case of only one planet did it seem possible to verify the prediction. Mercury alone is near enough to the sun to make the effect apparent. But in this instance the stage was all set to demonstrate the coincidence between theory and fact. Since Leverrier, in 1845, had pointed it out, astronomers had known that Mercury's orbit is advancing each century forty-two seconds of arc more than could be accounted for by the calculated gravitational attraction of other planets. On the basis of Einstein's theory, there should be an advance of forty-three seconds, which is indeed close to the actual advance of observation.

Theoretically, other planets should show similar advances. However, the amount in each case is so small as to be impossible of detection. As we recall, the reason for this astronomical circumstance is the increasing mass of a body with increasing velocity. A planet in its motion about the sun is alternately nearer to and farther from this central body. Therefore, its velocity will increase and decrease. According to Einstein's theory, its mass should also vary, thus altering the combined effect of the mutual gravitational influence between sun and planet. The result is a theoretical advance in the position of the planet's orbit. The almost complete coincidence of observation and theory in this instance solved a long-standing problem and at the same time gave wonderful support to Einstein. It was his first great victory.

Einstein's second triumph was more dramatic. It hinged upon the predicted deflection of a ray of light in passing through an intense gravitational field, such as that provided by our sun. But why should a ray of light be influenced at all? Upon what facts did Einstein base his claims? This should be readily apparent to one who has followed the developments of physics as sketched in the foregoing chapters. Light has been shown to be electromagnetic energy; the pressure of light has been experimentally demonstrated; therefore, it possesses mass, or inertia, and, since all mass is subject to gravitation, a ray of light in passing through the gravitational field of the sun should be bent out of its straight-line course. In other words, it should follow a geodesic through the time-space of that portion of the universe.

It will be perfectly understandable that, upon the basis of the present knowledge of the nature of light, even Newton's Law of Gravitation demanded that a ray of light should be deflected in a gravitational field. However, Newton's law called for a deflection just half as large as did Einstein's. In the test that was staged, the point to be determined was not whether there should be any deflection at all, but whether the amount of the deflection should agree with the law of Newton or with that of Einstein.

Such a test as was contemplated can be made only at the time of a total eclipse of the sun, and then only if there happens to be close to the sun stars, whose light in coming to the earth will pass through the sun's gravitational field. Eddington pointed out that the solar eclipse of May 29, 1919, would provide the essential conditions. Accordingly, despite the fact that at the time the eclipse expeditions were planned Einstein, whose prediction they were to test, was occupying a chair at the University of Berlin, in a country with which the British Empire was in deadly combat, the arrangements of the British astronomers went steadily forward. The vindication of scientific principles was placed above the storm and bitterness of international strife. One expedition went to Brazil and the other to the west coast of Africa. Photographs of the sun and of the stars in the immediate vicinity were taken. Several months later when the sun was not in that portion of the heavens, other photographs were taken. Then, the positions of the stars on the two sets of plates were compared. Very exact measurements with micrometers showed that the starlight had been shifted, thus giving additional proof that light does possess mass. Furthermore, the amount of the shift was found to be 1.60 seconds of arc on the African plates and 1.98 seconds on the Brazilian plates. The average is 1.79, not far from the 1.73 predicted in advance by Einstein. Newton's law called for a deflection of only 0.87 of a second. Since those historic expeditions, others have abundantly confirmed the Einstein view.

Does any one need to wonder why Einstein's views of the universe command respect? Behind them stands something more than the arbitrary creations of a brilliant intellect. They have found their counterpart in the fundamental realities of time and space. And may not this fact carry the suggestion at least that this is an intelligible universe, the product of creative thought? Only one other incident in the history of physics and astronomy, that of the discovery of Neptune, can compare in dramatic interest with this vindication of a famous prediction. Let us not lose sight of the fact, too, that the properties of time and space are not wholly independent of matter. This was the very basis of the Einstein contention, and it had seemed to find abundant confirmation.

Even yet, we are not at the end of this relationship between theory and fact. According to the Einstein hypothesis, another important circumstance should be true. To understand it, we must recall the structure of the atom and the way in which the formation of the spectrum colors is related to the periodic movements of the electrons. These movements produce the spectral lines with their definite positions in the scale of colors. Any slowing down in the rate of motion would shift the positions in the direction of a lower frequency and longer wave length, that is, toward the red end of the spectrum. In a sense, these periodically moving electrons are natural clocks, and it was Einstein's belief that in an intense gravitational field, such as that at the surface of the sun, the time they keep should run more slowly. This means that these spectrum lines, as compared with those obtained in a terrestrial laboratory from an artificial source, should be shifted toward the red. Although complicated by numerous conflicting factors, it is now generally conceded that this third prediction is confirmed by observation. This shifting of the spectrum colors, however, is not to be confused with that due to the well-known Doppler effect. In this latter case, the rapid motion of a star traveling earthward will cause the eye, or a spectroscope, to receive more light waves per second than it would if the star were stationary. This is equivalent to a higher frequency and results in a shifting of the spectrum colors toward the violet. When a star is receding from us, fewer waves are received per second, resulting in a lower frequency and a spectrum shift toward the red. As indicated above, this is not the effect predicted by Einstein. On his view, the motions of the electrons in their orbits are actually retarded by the exceedingly strong gravitation of the sun, thus reducing the rate of vibration of the electromagnetic waves. This would produce the same effect as that due to the receding motion of a star, and after making all allowances for the latter, astronomers believe that the Einstein effect has been proved, even in the case of the sun.

However, Eddington in his *Stars and Atoms* records a most striking confirmation of this portion of the Einstein theory. Astronomical observations indicate that the dark companion of Sirius is a small globe, not much larger in size than the earth and yet possessing a mass equal to four-fifths that of the sun. Regarding this determination of mass, Eddington says "it is one of the very best determinations of stellar mass." This makes the density of the star enormously large. Calculation shows it to be "60,000 times that of water—just about a ton to the cubic inch."

Now this unique member of the heavenly host seemed to offer a capital opportunity to test the third prediction of the Einstein theory and also to confirm the measurement of the star's mass. This was done by Professor Adams of the Mount Wilson Observatory, with the discovery of a large spectrum shift toward the red, just as had been anticipated. Furthermore, the amount of the shift was exceedingly close to the theoretical.

The Einstein theory won again. It still has hostile critics, but they seem to be in much the position of the old gentleman who contended that the earth is flat, and when told that the facts did not support his view, retorted, "So much the worse for the facts." The Einstein theory is as secure as Newton's Law of Gravitation, and probably more so. However, he has not deposed Newton. For all practical purposes, the sway of the Newtonian conception is as imperial as ever. Einstein has simply supplemented Newton with a larger and more complete view. In the subsequent years, their names are bound to be linked.

Another idea of Einstein's is exceedingly baffling. It is that of a finite universe. It has hitherto seemed impossible to conceive of the beginning or of the end of space. Clearly, it was infinite. What should we find at the limiting boundary, if not more space? And yet Einstein tells us that the universe is finite, but unbounded. Of course, he is thinking, not of ordinary three-dimensional space, but of this unpicturable complex of space-time. It is impossible to frame any mental conception of what such a condition would be like. However, we can use an analogy which may be helpful. We can imagine two-dimensional beings who have had no experience of any type of space, other than that of a simple extension in a flat plane. They know nothing of a third dimension, even as we are ignorant of the concrete reality of a fourth dimension. In their flat-land, parallel lines will never meet, and no straight line will ever return to its starting-point. They imagine that the surface of their plane is of infinite extent. However, the surface of a sphere offers an example of a two-dimensional area that is finite but unbounded. An insect could roam upon its surface, as we may do upon the earth, without ever finding a boundary, and yet it might return to its starting-point. Just as two-dimensional beings would find it difficult to conceive of a world of three dimensions, so do we experience a similar difficulty in trying to picture a finite universe of four dimensions.

Dr. Edwin Hubble said not long ago in addressing the Astronomical Society of the Pacific that "space is not limitless—there is a boundary to the universe. An infinite homogeneous universe is not possible. We can set certain vague limits and say that from the modern speed of the planets and stars and from the blackness of the skies, a homogeneous universe could not extend more than 10,000 billion light years. This space, however, has no definite boundaries such as a surface like that which encloses the earth. It is bounded by a conception of general relativity and is a four-dimensional structure of space and time with a definite volume."

Perhaps, we shall have to let it go at that. Starlight, then, after an inconceivably long period of time, placed by Jeans at 500 billion years, would circumnavigate the universe and return to its starting-point, barring deflections by its passing near to strong gravitational fields. After all, the idea of a finite universe is no more difficult to believe than is that of curved space. Einstein has been proved right on so many fields that it would be a rash layman, or scientist, who would declare him wrong in this.

One other point which Einstein emphasizes regarding this finite universe is the dependence of space upon matter. The idea that space could exist as a great empty void with nothing in it is false. Space without matter is an impossibility. If more matter should be created, the universe would automatically expand. If matter is being dissipated, as many believe, space is shrinking in size. When the last particle of matter disappears, space will go with it. The universe will absolutely be on the "rocks." Such is the conception of Einstein.

EINSTEIN'S LATEST ANNOUNCEMENT

Early in 1929, the world was fairly startled by the report from Germany that Einstein was about to announce a far-reaching addition to his renowned theory of relativity. Popular interest was deep and wide spread. The public in general, not only scientists, but men in every walk of life, awaited further information with a keenness that was impressive. Not since the days of Volta and Davy had enthusiastic anticipation run so high. Although Einstein himself had said in advance that "probably not more than a dozen or so men in the world could possibly understand" him, the scientific ardor was not dampened. The manuscript containing the announcement was said to cover but five pages, yet it represented ten years of work. And the general public clamored that he explain his doctrine in general terms—in simple, plain English, German and French. The advance statement, couched in the severest mathematical language—symbols which only the elect could interpret and understand—was cabled to this country and printed as news, symbols and all, in the metropolitan dailies. An item in one of these, headed "London," says, "The most conspicuous British reaction to the publication of details of the new Einstein theory was a three-column cartoon in 'The Evening News' to-day, showing the framers of the British income tax laws bowing low and taking off their hats before the professor as the new master of incomprehensibility."

The significance of Einstein's labors lies in his attempt at a correlation, although as yet it be only a formal one, of gravitation and electromagnetic phenomena. Hitherto, there has existed a wide gulf between these two aspects of fundamental reality. On the basis of the new Einstein equations, electromagnetism becomes the property of space, just as gravitation did before it. Professor Thomas H. Gronwall, of Columbia University, in speaking of the accomplishment, said, "Einstein has now succeeded in finding a mathematical basis common to the two sets of formulæ, and the great beauty of his work is that it is so simple." At a point where the universe, or at least our knowledge of it, seemed to be out of joint, Einstein has bridged the gap. This new triumph suggests that a fundamental unity, a controlling rhythm, like the harmony of a musical composition, may run through all the diverse manifestations of physical science. And yet, we must not infer that Einstein has identified gravitation and electromagnetism. What he has done is to unify the mathematical treatment of electricity and magnetism and of gravitation. It suggests a strong bond of kinship between the two sets of phenomena. It is an opening wedge, an initial discovery, which may lead to the formulation of a single fundamental law governing in every province of Nature's realm.

In speaking of this achievement editorially, *The New York Times* said, "What the practical effects will be, no one can foretell. But it is conceivable that, as the Copernican theory has undoubtedly had some influence in promoting a consciousness of the common interest of the human race on a planet swinging apart in space and in extending a monotheistic view of creation and Providence, so this unity of law, if confirmed in the highest courts of research, should not only give a new peace to restless minds seeking the 'rational whole' but strengthen the sense of solidarity among creatures subject to it."

THE MAN HIMSELF

The pen-portraits of Einstein, written by those who know him, show that he is an altogether human individual. He combines the intellectuality of an extraordinarily keen scientific mind with the soul of the artist. He finds relaxation from the abstract realms of research, where he wanders much alone, in music. A favorite recreation is to improvise on the piano, and he is a violinist of ability, revealing the tastes of the classicist. This side of his nature is disclosed in the following words, "First of all I believe with Schopenhauer that one of the most powerful motives leading toward art and science appears in the form of a desire to fly from the workaday life with its painful roughness and dreary wilderness, from the chains of the ever-changing desires. It drives the more sensitive mind away from personal existence in a world of objective seeing and understanding. It might be compared with the longing that draws the citizen from his noisy, entangled surroundings toward the quiet mountains where his far-reaching gaze penetrates the clear air and follows restful forms which seem to be created for eternity. But to this negative notion is added a positive one. Man tries to form a simplified and clear conception of the world in a manner somehow adequate to himself, and to conquer the world of reality by replacing it to a certain extent by this picture. The painter, the poet, the speculative philosopher, and the naturalist do it, each of them in his own way. He places in this picture the center of gravity of his emotional life in order to find the tranquillity and constancy which he can not find within the narrow circle of turbulent personal experience."

Bernard Shaw, in sending a message by a friend, said, "Tell Einstein that, if appearances go for anything, he is really a musician masquerading as a scientist."

Einstein was born at Ulm on the Danube, Würtemberg, in 1879. Later, he became a naturalized Swiss citizen and has remained such until the present. As a lad, he disliked languages, literature and history, but was particularly fond of mathematics and science. At thirteen, a friend of those years tells us, he was a master in higher mathematics and in philosophy he was reading Kant. He grew up in a home, "blessed with quietness, serenity and comfort," and was given every advantage of education. After becoming a Swiss citizen in 1901, he served for a time as an official in the Patent Office of that country. However, his genius as a scientist gradually came to be recognized, and he was called to the teaching profession, in which he has occupied chairs at the Universities of Bern, Zürich, Prague and Leyden. Since 1914, he has been associated with the University of Berlin, in a capacity which enables him to devote his entire time to research. He has the privilege, but not the obligation, to teach. Theoretical physics is his particular field.

In speaking of the genesis of his theory of relativity, Einstein has said, "The first stage, the special theory of relativity, owes its origin principally to Maxwell's theory of the electro-magnetic field. From this, combined with the empirical fact that there does not exist any physically distinguishable state of motion which may be called 'absolute rest,' arose a new theory of space and time. It is well known that this theory discarded the absolute character of the conception of the simultaneity of two spatially separated events. Well known is also the courage of despair with which some philosophers still defend themselves in a profusion of proud but empty words against this simple theory."

And, if Einstein declares that his theory is "simple," no one should say him nay.

Sensitive and retiring by disposition, Einstein shuns publicity. He finds the greatest difficulty in understanding why people should be so interested in the products of his creative mind. He does not fully appreciate that deep down, underneath the apparent superficiality of this heterogeneous mass of seething humanity, throbs a strong and abiding yearning for larger knowledge, broader horizons, deeper insights. And it is because Einstein, more than any one else in two centuries among scientists, has seemed to be knocking successfully at the door of Nature's deepest mysteries that people listen with more than ordinary interest to whatever he may have to announce. To have achieved such a position in the thought of this generation is a tribute to the man, second to none other, and immensely creditable to his fellow men.

CHAPTER IX

Physical Discovery and the Heavens

CLOSE ASSOCIATION OF PHYSICS WITH CELESTIAL PHENOMENA—RECEDING HORIZONS—STELLAR POPULATION—SHAPE OF OUR OWN GALAXY—A COSMIC DAY—ISLAND UNIVERSES—LIFE IN THE UNIVERSE—VIEW OF JEANS—ANALYZING THE STARS—DEVELOPMENT OF THE SPECTROSCOPE—FRAUNHOFER LINES—DISCOVERIES OF BUNSEN AND KIRCHHOFF—INTERPRETATION OF FRAUNHOFER LINES—LOCKYER'S DISCOVERY OF HELIUM—RADIANT ENERGY OF THE STARS—SOURCE OF SOLAR ENERGY—EARLY THEORIES—SIGNIFICANCE OF ELECTRICAL STRUCTURE OF MATTER—EQUIVALENCE OF ENERGY AND MASS—EINSTEIN'S EQUATION—ANNIHILATION OF MATTER—TEMPERATURE OF A STAR—SIXTY TONS OF SUNLIGHT—COSMIC RAYS—MILLIKAN'S WORK—BIRTH OF ATOMS—A COSMIC CYCLE—POSSIBILITY OF LIFE AGAIN—NEW LIGHT ON SECOND LAW OF THERMODYNAMICS—OTHER VIEWS.

That the science of physics should be part and parcel of the phenomena of the celestial spaces should be no surprise to one who is acquainted with the work of Newton or who possesses the most elementary introduction to Einstein's theory of relativity. Even on the basis of the old definition of physics as the science of energy and matter, it was essential to any knowledge of what transpires in the heavens. And with energy now usurping the leading rôle, it is no less so. The tools which the astronomer uses in his exploration of space are those of physics—the telescope, the spectroscope, the spectro-heliograph. And they are of an extraordinary degree of precision. Dr. Edwin Hubble tells us that the great Mount Wilson reflector could detect the light of a candle at five thousand miles, or that of an arc-light at the distance of the moon. The bolometer measures a temperature so slight as one ten-millionth of a degree. Distances, dimensions and motions are accurately measured with the micrometer. Consider the twentieth-century triumph of being able to measure with precision the change in direction of a point seventy miles away when the observer moves his instrument along a base-line a single inch. And photography has increased the stellar population by countless millions. To-day, these instruments are making possible an acquaintance with the great Island Universes, our nearest neighbors in space, outside the system of the Milky Way. The present-day conclusion that the universe is finite is the product of physical research. On this point, Hubble, already quoted in this connection in another place, says, "Yet it [the universe] cannot continue indefinitely. An infinite homogeneous universe is not compatible with the laws and the phenomena of nature. The best working hypothesis of the day, the general theory of relativity, postulates a universe which is finite. The dimensions can be calculated in a tentative way, by assuming the observable region to be typical of space in general. It then appears that we are actually observing an appreciable, though very minute, fraction of the entire universe. Such is the present status of the explorations of space—our adventures in cosmography. A definite region has been sketched in outline, a definite boundary established, at least as a working hypothesis, and astronomers are now proceeding with the task of mapping in the details."* Let us survey with the physicist this vast domain of time and space, of which we chance for the moment to be citizens.

Across the centuries that separate us from the ancients, tending their flocks beside the Nile and the Euphrates and studying the stars by night, we have seen the frontiers of the universe recede on ever-widening horizons and our conception of its magnitude and structure sustain revolution after revolution. The snug little universe of the Greeks, with its cramped boundaries and its prodigious feats of daily revolutions vanished with the coming of Copernicus.

**Harper's Magazine*, May, 1929.

The earth was deposed from its central position of majesty and influence. It was reduced to the position of a mediocre subordinate in a solar system which recognized the sun as the arbiter of its destinies. For long, it flattered the vanity of earthly mortals to believe that our sun occupies a central position in the great galaxy of the Milky Way, our own island universe. Recent researches, however, show that we are approximately 50,000 light years away from this celestial center, and this unit, the distance light will travel in a year at the rate of 186,000 miles a second, is equal to six trillion miles. The haughty pride of the ancients has been humbled. Ephemeral creatures of but the tiniest fraction of a cosmic moment, the human race may be no more than a pawn on the chess-board of time and space, a fragment of life adrift upon this bit of earth and sea and sky. Yet, its knowledge widens as the horizons of the universe recede. For all we know, an intellectual rulership may be replacing the majesty of a central position.

What is the stellar population of our own galaxy, the system of the Milky Way? Estimates vary from ten billion to more than forty billion. Dr. Edwin B. Frost, Director of the Yerkes Observatory, in *The Century Magazine*, for March, 1929, says, "About ten years ago, an estimate based on counts of the stars on a photographic chart of the heavens, placed the number at fifteen hundred million. We are now obliged to increase this number thirty-fold —to more than forty billion. To reach this estimate, photographs are taken of small sample areas well distributed over the sky. Counts are made of the number of stars of each separate magnitude, from the bright stars down to the faintest that can be seen on the plate, stars of the twenty-first magnitude. . . . A formula can then be derived expressing the relationship thus found between numbers and brightness. Then *if*, and it is a big if, the formula holds true for the stars beyond the reach of our telescopes, the whole number of stars to the faintest imaginable magnitude can be mathematically computed." The total of the number of stars that can be seen with the naked eye from all positions is a paltry five thousand. And beyond our own galaxy are millions of other galaxies, each replete with its quota of suns.

When we consider dimensions, figures are equally astounding. Astronomers are generally agreed that the galactic space enclosed within our own stellar system is in the shape of a gigantic watch. Of it, Dr. Harlow Shapley, of the Harvard Observatory, says, "So huge is this watch that it takes light, traveling 186,000 miles a second, or 6,000,000,000,000 miles a year, 3,000 centuries to traverse its diameter and nearly 1,500 centuries to cross its thickness." Our sun is a mere pigmy among giants. Into a star like Betelgeuse, twenty-five million stars of the solar type could be packed with ease. However, Betelgeuse lies near the limit in this direction. A star much larger would be an Einsteinian impossibility. Such a monstrosity would become "topheavy," disrupted by gravitational stresses and excessive temperatures, its substance strewn along the byways of the celestial spaces to afford the primordial stuff out of which star-building might begin anew.

This immense galactic system, too, is in motion, albeit relative motion. The idea of "fixed stars" is a fiction of less well-informed eras. The thin watch-like disk of far-flung area appears to be revolving about a mysterious center far away in Sagittarius with a velocity calculated to be more than two hundred miles a second. Even at this velocity, ten times greater than the orbital speed of the earth about the sun, it requires three hundred million years for the galaxy to make one rotation on its axis. This period might be called a cosmic day, and it is suggested that six such days "might be a reasonable time for the evolution of a world."

Thus far, we have considered in this sketch of the heavens only the stars of our own system of the Milky Way. Beyond it lie the great spiral nebulæ, wisps of mellow light, mostly invisible to the naked eye, yet revealed by modern methods of investigation to be island universes comparable to that of which we chance to be inhabitants. Hubble estimates that there are ten million nebulæ within reach of the one-hundred-inch reflector, and he places their average distance in the order of two hundred million light years. Surely, in describing the universe as "finite," we shall have to soft-pedal the conception. And when the forthcoming two-hundred-inch reflector arrives, distances will lengthen, horizons will recede once more, new provinces will be brought within the starry folds and the flag of the universe will float over a domain of unimaginable extent. Thus, we seem to be citizens on a tiny planet of a puny solar system, an insignificant unit in an immense galaxy, which turns out to be but one in a vast federation of other galaxies.

In passing, let us note that this new two-hundred-inch reflector will be fully ten times as powerful as its immediate predecessor. It will penetrate three times as far into space and will open up a vast new realm of the hitherto unexplored celestial domain equal to thirty times the volume of that now known. A marvelous product of applied physics will this immense instrument be.

And what of life in this universe? Is our little earth the only spot where evolution has flowered into organic life? Regarding this most fascinating subject of speculation, Professor J. H. Jeans, eminent Scottish astronomer and physicist, says, "It is difficult to imagine life of any high order except on planets warmed by a sun, and even after a star has lived its life of millions of millions of years, the chance, so far as we can calculate it, is still about a hundred thousand to one against its being a sun surrounded by planets. In every respect—space, time, physical conditions—life is limited to an almost inconceivably small corner of the universe."*

**Nature*, reprinted in *Annual Report of the Smithsonian Institution*, 1927.

Among a stellar population reckoned in billions, a hundred-thousand-to-one chance would provide innumerable centers of life and growth. Somehow it seems as though the universe would be out of tune if ours were the only planet in time and space where life has appeared. As naturally as harvest-time brings the ripened grain, many a sun at the appropriate season must become the center of manifold populations. But, of course, we can only conjecture. Again, Jeans says, "What, then, is life? Is it the final climax toward which the whole creation moves, for which the millions of millions of years of transformation of matter in uninhabited stars and nebulæ, and of waste radiation into desert space, have been only an incredibly extravagant preparation? Or, is it a mere accidental and possibly quite unimportant by-product of natural processes, which have some other and more stupendous end in view? Or, to glance at a still more modest line of thought, is it of the nature of a disease which affects matter in its old age, when it has lost the high temperature and capacity for generating high-frequency radiation with which younger and more vigorous matter would at once destroy life? Or, throwing humility aside, is it the only reality, which creates, instead of being created by, the colossal masses of the stars and nebulæ and the almost inconceivably long vistas of astronomical time? There are too many ways even to enumerate of interpreting the conclusions we have reached; I do not, however, think there is any way of evading them."*

Marvelous as are the acquisitions of knowledge made possible by the telescope and its accessories, there is no probability that they will ever be able to reveal life in other worlds than ours. Unique and alone, as far as we shall ever know, solitary sojourners in a wilderness of stars, men may here continue to come and go until the sun grows cold and the earth becomes a derelict on the seas of time and space.

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I happen to be writing on the fifteenth anniversary of the beginning of the Great War. *The New York Times* in an editorial takes advantage of this circumstance to picture vividly the immense distances of the spaces about us. The editorial says, "There is somewhere in the heavens a star which the news of the day 'which waked all Europe to war,' Aug. 5, 1914, reached only this morning, though it has traveled at the speed of light continuously for fifteen years. There it was only last night at 11 o'clock that England declared a state of war to exist. The inhabitants of that star, eight light-years beyond Sirius, would be seeing this morning the Germans shelling Liege and Namur and crossing the French border at Mars-La Tour and Moinville; the Lusitania putting out to sea from the harbor of New York, and the Cecile creeping back to Bar Harbor; England's envoy leaving Germany and General Joffre setting out from Paris for the front; the Tennessee taking on a cargo of gold for stranded Americans abroad; the yacht Resolute capturing a cup; the Cubs being beaten by the Giants and the Yanks kept from scoring; the Summer colony dancing in picturesque costumes at Narragansett Pier and a Federal inquiry dragging on wearisomely in New Jersey. H. G. Wells would be seen or read writing Armageddon, and President David Starr Jordan by an ironical fate traveling somewhere in Europe en route to an international peace congress in Vienna. To imagined inhabitants on still more remote stars that August day in 1914 has not yet dawned. By those in the most distant stars its light that roused Europe on that fateful morning will not be seen for yet millions of years, by which time our planet may have ceased to wander in the skies or its inhabitants will have ceased to remember this conflict except as a primeval war that led to a world effort to settle disputes in another way."

The light beams which our telescopes may trap to-night from the distant nebulæ left their sources when our earth was still in the heyday of vigorous youth and countless millennia before man appeared upon its surface. When the light waves which are just now leaving those inconceivably remote parts reach this point of space, the human race may long since have ceased to be, become but a memory, a transient episode in the evolution of stars and atoms.

ANALYZING THE STARS

Who has not seen on floor or wall patches of color where sunbeams have chanced to fall upon an angular piece of glass? And the rainbow, the spectrum painted by sunlight in passing through falling drops of water, was for ages an object of awe and admiration. As we have seen, not until the coming of Newton was the composition of sunlight discovered. Even he did not foresee that knowledge of this simple phenomenon would lead to the invention of the spectroscope, a more amazingly sensitive device for the detection of exceedingly minute quantities of the chemical elements than the boldest scientist had ever dreamed possible. With it, so small a quantity as one two-hundred-thousandth of a grain of sodium may be detected with perfect ease. Furthermore, it makes no difference whether the substance being analyzed is in the laboratory or in a distant star. The spectroscope, therefore, makes it possible literally to bring the stars within the laboratory. That this universe is everywhere built from the same primordial elements is now a scientific certainty. Could we take the wings of the morning and fly away with the velocity of light forever and a day, nowhere should we find any new elements. Quite recently, Professor I. S. Bowen, of the California Institute of Technology, has shown that the hitherto hypothetical element designated as nebulium is due to atoms of nitrogen and oxygen in the distant stars, stripped by the terrific temperatures and pressures of their outer electrons. That is, the universe seems to be homogeneous, uniform, to be built on one fundamental plan of cosmic architecture. And these discoveries are largely the revelations of the spectroscope.

The preliminary work leading up to the invention of this now indispensable instrument of the laboratory began with Thomas Melvill, a divinity student at Glasgow, who died at the early age of twenty-seven. In 1752, he made the first observations of spectral lines. Time and again, we have had occasion to refer to the electronic movements within the atom which cause each element to produce a bright-line spectrum of perfectly characteristic colors and position. Furthermore, it is easily seen that light, whatever its source, may thus be analyzed. That this light may have come from the remotest parts of space or may have been a million years on the way makes no difference. The telltale spectral lines will, in every instance, declare the kind of atoms that gave them birth. These messengers of light, whatever may be the medium of transmission, preserve for untold ages across the intervening abyss of space-time the indelible impress of their chemical origin.

Following Melvill in this pioneer work came William H. Wollaston, a London physician, who bears something of the same relation to the scientific discoveries of his time (1766-1828) that Robert Hooke did to those of the previous century. He was a pathfinder, but not a builder. He originated important lines of research, but did not develop them. In the field of spectrum analysis, he fell just short of a crucial discovery.

The man who finally did follow up these trails in earnest was Joseph Fraunhofer, whose name has been immortalized in connection with the dark lines of the solar spectrum, which he was the first to observe. Although he died in 1826, at the age of thirty-nine, he accomplished much. He was a native of Bavaria, the son of a poor glazier, in whose trade he served an apprenticeship. As a skilled glass-grinder, he secured a position in an optical institute in Munich, where he became a member of the Academy of Sciences and conservator of its physical cabinet. There he invented improved machinery and devised new methods and measuring instruments for grinding and polishing lenses. He produced optical glass of a superior quality and learned how to compute accurately the forms of lenses.

In particular, this man was interested in making "achromatic" lenses, that is, lenses free from the color defects of the earlier years. In doing so, he produced and studied spectra, color scales, from various sources. One day, in the spectrum from the light of a lamp, he discovered a double line in the yellow portion of the color band. This is now known as the sodium line, being produced by that element, and it is the most prominent of any of the spectral lines. Further observation led to the discovery of this line in the light from other sources, and always "exactly in the same place." Then he examined sunlight. He says, "I wished to find out whether a similar bright line could be seen in the spectrum of sunlight as in the spectrum of lamplight, and I found, with the telescope, instead of this, an almost countless number of strong and feeble vertical lines, which, however, were darker than the other parts of the spectrum, some appearing to be almost perfectly black." Fraunhofer then examined starlight, and in the reflected light from Venus recognized some of the solar lines. He, too, prepared the first diffraction gratings for producing spectra and with them made the earliest determinations of wave lengths, obtaining results remarkably accurate, considering the primitive tools with which he worked.

Although he had discovered the "Fraunhofer lines," this Munich maker of lenses did not unravel their meaning. He died without foreseeing the rôle that they were to play in chemical analysis and in the explorations of the heavens. Passing over several intermediate discoveries of minor importance, we come to Robert Wilhelm Bunsen and Gustav Kirchhoff, who early in the second half of the last century unveiled the mystery of the spectral lines and invented the first practical spectroscope. At the time they carried out the investigations leading to this epoch-making interpretation, Kirchhoff, the physicist, and Bunsen, the chemist, were professors at the University of Heidelberg.

In a small room of an old building, the "Riesengebäude," then a century and a half old, they conducted their researches. Illuminating gas had but recently been introduced there, and Bunsen had invented the famous gas burner, which has immortalized his name in every laboratory of the world. The non-luminous gas flame provided by this played a large part in their discoveries.

In this flame, they vaporized many chemical substances and viewed with the spectroscope the colors obtained. This instrument consists essentially of three parts—a means of focusing rays of light upon a triangular glass prism, the prism itself to disperse the light into its component colors, and a small observation telescope with which to magnify the spectrum produced. In a short time, these men had made the fundamental discovery that each element gives rise to a characteristic bright-line spectrum, all its own.

Then one day in 1859, it was found that dark lines in place of the bright ones are obtained when a light of sufficient intensity from another source is allowed to shine through the gas flame containing elements in a state of incandescent vapor. Kirchhoff immediately drew the conclusion, and it was the correct one, that the colors produced in the gas flame neutralize in the light passing through them precisely the same wave lengths which they themselves emit. Therefore, where the bright lines previously were, there is an absence of color, or in other words, dark lines.

This discovery at once gave a clue to the mystery of the Fraunhofer lines. Hundreds of these dark lines in the solar spectrum had been mapped. Now their meaning was as clear as day. The solid photosphere (light-giving surface) of the sun sends out all wave lengths of the visible octave of the color scale. However, to reach our telescopes and spectroscopes this light must pass through the sun's atmosphere, in which most of the elements exist in the form of incandescent vapor. Just as in the laboratory, when light from some other source shines through the incandescent vapors of the gas flame, here, too, neutralization of wave lengths occurs, resulting in dark lines crossing the sun's spectrum. When certain of these dark lines coincide, as they do in many cases, precisely with those obtained in the laboratory for a particular element, it becomes certain that this element exists in the atmosphere of the sun. Thus, we may analyze the elements in the sun, ninety-three millions of miles away, as exactly as though we should bring its substance within the retorts and crucibles of our laboratories.

The spectroscope also enables us to detect with equal certainty the composition of the stars and nebulæ. Furthermore, it tells much regarding their physical states and motions. A bright-line spectrum, instead of a continuous one, indicates an incandescent gas. As we have seen in the chapter on Einstein, a shifting of the spectrum toward the violet shows motion of the star toward us; a shift toward the red indicates a receding star.

Almost immediately, this instrument in the hands of its inventors disclosed two new elements—cæsium and rubidium—in the mineral water at Dürkheim. Bunsen and Kirchhoff jointly share the credit for the development of the spectroscope and its adaptation to chemical analysis in the laboratory. However, it was Kirchhoff alone who seized upon this invention to make the stars yield a knowledge of their compositions. He it was who explained the Fraunhofer lines. Regarding this interpretation, Helmholtz said: "It had in fact most extraordinary consequences of the most palpable kind, and has become of the highest importance for all branches of natural science. It has excited the admiration and stimulated the fancy of men as hardly any other discovery has done, because it has permitted an insight into worlds that seemed forever veiled for us." In referring to this discovery, Kirchhoff is said to have frequently told the following story: "The question whether Fraunhofer's lines reveal the presence of gold in the sun was being investigated. Kirchhoff's banker remarked on this occasion: 'What do I care for gold in the sun if I can not fetch it down here?' Shortly afterwards Kirchhoff received from England a medal for his discovery, and its value in gold. While handing it over to his banker, he observed, 'Look here, I have succeeded at last in fetching some gold from the sun.'"

The spectroscope was scarcely a decade old when Sir Norman Lockyer, in exploring the heavens with it, discovered helium in the atmosphere of the sun. Helium was not then known among the terrestrial elements, and a generation was to pass before Sir William Ramsay found it issuing from certain minerals and as one of the rare gases of the earth's atmosphere. No one then dreamed that in a few years we should be filling our airships with it. Next to the telescope, the spectroscope has been chiefly instrumental in making the heavens as an open book. Without it, much that is now commonplace would still be numbered among the veiled mysteries.

It was just preceding the invention of the spectroscope that Melloni established the identity, save in wave length, of heat rays and light rays. Of his early interest in this field, he says, "I was born at Parma (Italy), and when I got a holiday used to go into the country the night before, and go to bed early, so as to get up before the dawn. Then I used to steal silently out of the house, and run, with bounding heart, till I got to the top of a little hill, where I used to set myself so as to look toward the east. . . . Nothing so rapt my imagination as the bond, so intimate, which unites the phenomena of life to the brilliant star of day."

THE RADIANT ENERGY OF THE STARS

Whence comes the energy of the stars, radiated throughout space so abundantly, so lavishly, chancing here and there to do a little useful work upon some planet, but for the most part traveling, as it seems, toward some unknown, purposeless goal? This question-mark has cast its shadow across the pathway of every generation of scientists, and not until the present have we seemed to find a satisfactory answer. The ancients imagined that intense combustion accounted for the celestial fires; Sir Norman Lockyer believed that the impacts of swarms of meteors upon the surface of the sun were sufficient to maintain the solar heat; then came Helmholtz and Lord Kelvin with their contraction hypothesis. In the case of the sun, they showed that a slight shrinking of the solar mass under the influence of gravitation would maintain its heat for a very long time. A shrinkage of one hundred and twenty feet a year, the cumulative effect of which could not be detected with our most powerful telescopes in less than ten thousand years, would turn the trick. However, this theory soon ran into snags. "A very long time" is susceptible of various interpretations. It is a matter of relativity. It means one thing in human affairs and something else among the stars. On the basis of this theory, the age of the sun, from birth to now, seemed not to have been more than twenty million years. In the case of the diffuse stars of high luminosity, the situation was simply impossible. At their prodigious rate of heat radiation, the life of a star could not be more than about one hundred thousand years. Even here on the earth, geologists and biologists began to growl over the cramping time-limit. In fact, most of them ignored it. It did not seem possible that the sun could generate sufficient energy to maintain life here for more than twenty millions of years longer. This was a terrific bomb to cast into an otherwise peaceful camp. Actually some people began to worry. I presume they were believers in the doctrine of reincarnation and thought that they might return to earth again at that particularly inauspicious moment of cosmic evolution, twenty millions of years hence.

As we have seen, too, the facts of radioactive disintegration of minerals points to an age of the earth's crust of not less than a billion years, probably a billion and a quarter. Clearly, the contraction hypothesis, never satisfactory, would not do in the light of twentieth-century knowledge. However, the very research weapon which dealt it the death blow provided, together with Einstein's theory of relativity, a way out of the difficulty.

With the establishment of the concept of the electrical structure of matter, it became clear that matter should be theoretically convertible into energy. Indeed, matter seemed to be but the most general form of potential energy. Energy, too, in the form of electromagnetic waves had been shown to possess inertia, the other name for mass and the most general property of matter. The pressure of light had been demonstrated. Indeed, as Eddington says, "Theoretically, it would be possible to knock a man over by turning a searchlight on him—only the searchlight would have to be excessively intense, and the man would probably be vaporized first." It had been shown, too, in the case of electrons that the mass increases with velocity, that is, with increase of kinetic energy. Kinetic energy thus seemed to be convertible into mass. More than ever, energy became synonymous with matter. The evolution of heat seemed to necessitate a decrease in mass. More significant than all else, Einstein in his Special Theory of Relativity had shown the theoretical equivalence of energy and mass, and had worked out the exact formula governing the transformation. It turned out that the energy in any such conversion is equal to the square of the velocity of light times the quantity (mass) of matter transformed. Thus the whole matter was reduced to the barbarous, but beautifully expressive, language of mathematics. In any given case, it became possible to calculate both the mass and the energy involved. It seemed that matter as such might be annihilated with the liberation of vast quantities of energy. And where might there be a more plausible place to look for the practical operation of this process than in the cosmic crucibles of the stars?

This annihilation of matter is now the orthodox view among scientists as to the origin of the radiant energy of solar fires, and there seems to be no question as to its correctness. Regarding this, Jeans says: "Throughout a star's interior electrons and protons must at intervals fall into one another and mutually destroy one another, the energy of their fall being set free as radiation. The energy of this fall is enormous, being sufficient to set both the masses involved into motion with a velocity of 0.866 times that of light. In no other way can a given mass of matter be made to yield energy of amount comparable with this; for example, whereas the ordinary combustion of a ton of coal provides energy enough to drive an express locomotive for an hour, the annihilation of a ton of coal would provide enough energy for all the heating, lighting, power, and transport in Great Britain for a century. Each proton or atom, as it is annihilated, makes a splash of radiant energy which travels through the star until, after innumerable absorptions and reemissions, it reaches the star's surface and wanders off into space."*

Here, too, Jeans has given a picture of the mechanics of the process. The equal and opposite electric charges of an electron and a proton neutralize each other, thereby canceling the form of matter under which they were masquerading and converting it into its other self—energy. Thus, matter is seen to lead a double existence.

The methods of modern physics make possible the measurement of the temperature of a star, both at its surface and in its interior. The surface temperature of the sun is 6000 degrees Centigrade, nearly equaled by a Sperry search-light here on the earth, while the temperature at the center rises to 40,000,000 degrees. Although the production of this celestial heat is due to the actual annihilation of electrons and protons, the degree of heat, or temperature, indicates the rate of motion of molecules, atoms and roving electrons, detached from their planetary orbits about the

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*Nature, reprinted in *Annual Report of the Smithsonian Institution,* 1927.

central nuclei. While the prosaic movement of the molecules of air in a room at normal temperature averages only 500 yards a second, the mad phantasmagoric dance within a sun leads them to the merry tune of 100 miles a second. However, inasmuch as the beta particles shot from radium approach the speed of light, this speed of the energy units in the center of the sun is after all rather ordinary. Even the meteors coming into the earth's atmosphere from outer space travel with velocities ranging from 10 to 100 miles a second.

Suppose we start at the center of the sun, nearly a half-million miles from the surface, and work outward, observing what happens along the way. The intense battering action of atoms upon one another shakes electrons loose from their orbits. These electrons speed away at enormous velocities, leaving the parent atoms in an ionized state, that is, lacking their full quota of planetary units. Presently, an electron collides with a dismembered atom, slipping into an outer orbit and at the same time giving rise to an X-ray. The X-ray begins to travel outward with the speed of light, but in the merest fraction of a second its energy is sucked up by an electron in an orbit of some atom, releasing the electron, which repeats the foregoing history, over and over without end. Prodigious quantities of X-rays are continually being generated deep within a sun, which by repeated transfers of energy are incessantly disappearing and reappearing. Finally, after countless billions of combats and a period of many centuries, these X-rays, alternately losing their identity and living again in their successors, make their way to the surface. There, their wave lengths increase and they are transformed into ordinary light and heat waves, which begin their journeys through space. At numerous points, too, we observe the annihilation of electrons and protons through the neutralization of their charges, thus giving rise to vast quantities of energy of an exceedingly short wave length, which also makes its way to the surface for radiation into space.

Astrophysicists undoubtedly know with a high degree of accuracy what takes place within a star. The electronic movie has disclosed its secrets.

SIXTY TONS OF SUNLIGHT

We may now speak of a ton of sunlight with as much propriety as we designate a ton of coal or a pound of beefsteak. Sunlight possesses inertia, mass. In other words, it is weighable. Furthermore, it is the product of the transformed mass of the sun. And that is what we mean by "sixty tons of sunlight." That represents our annual drawing account in the bank of solar energy. Sixty tons of the sun's mass are dissipated each year for the benefit of the life and energy processes of our planet. Sixty tons of sunlight, therefore, are all that stand between us and a cold, dead, dreary world.

Eddington has shown that to maintain the solar fires the sun loses by annihilation of electrons and protons one hundred and twenty billion tons of its mass each year. Of the resulting energy radiated into space, our earth intercepts about one two-billionth. Thus, by a simple calculation, we arrive at the above figure as the number of tons of energy available each year for use on this planet.

We wonder how long our central luminary will be able to withstand so prodigious a drain upon its substance and still radiate sufficient energy to maintain life down here. In view of the temporary scare created by Lord Kelvin, it is comforting to know that not for fifteen billion years yet will it be necessary to consider the feasibility of closing out business on this planet and tacking a "To Let" sign on the entrance. Certainly, this is a sufficiently long draft upon the bank of futurity to reassure the most timid soul. If man's tenure upon the earth is to be fifteen billion years and he has as yet lived barely half a million, he has heard scarcely a single tick of the cosmic time clock. What evolution may do to him before the expiration of his sentence, no one can have the faintest conjecture.

But let us return to the sixty tons of sunlight. This allotment of solar energy means about one-sixth of a ton per day, or a little less than a quarter of a pound a minute. In other words, to maintain our little earth as a going concern it is necessary that something less than four ounces of the sun's mass be converted into energy each minute and be relayed in some manner across the ninety-three millions of miles of intervening space to be translated in some small measure into life and useful work. The precise figure is 0.231 pounds.

Suppose we substitute this quantity in the Einstein formula for the conversion of mass into energy. If we work out the result we shall find that this apparently insignificant quantity of solar matter yields the inconceivably vast amount of two hundred and thirty-three quadrillion foot pounds of energy per minute. Since thirty-three thousand foot pounds per minute make a horse-power, we soon discover that the continuous power output of the sun intercepted by the earth reaches the amazing total of six trillion seven hundred and sixty-five billion. This is equivalent to the power of ten million Niagaras rolled into one. To obtain the same amount of energy through the burning of coal would require an annual output nearly twenty times as great as the total quantity contained in this country when the white man first stepped foot upon these shores. It is forty-five times as much as is used in the whole world for all mechanical power purposes whatsoever. To supply the amount of energy in the sunlight captured annually by food plants everywhere would require the burning of eighty-nine hundred times as much coal as the world now produces. The sunlight falling upon the United States in a minute, if utilized without loss, would meet our entire energy requirements for a year. The solar energy absorbed by the glistening sands of the Sahara Desert in a day is equivalent to the radiation from the combustion of six billion tons of this crystallized sunshine of a former geologic era.

Thus sixty tons of sunlight a year constitute the magic formula which spells life and happiness upon this planet.

One aspect of this picture is somewhat disquieting. This loss of the sun's mass means that its gravitational influence becomes constantly less. Jeans estimates that because of this loss the earth in a century slips a little more than a yard farther away from its attracting center. In a million million years, we shall be nine million miles more distant from the sun than we are now. At that time, the sun, too, will have spent six per cent. of its substance. The combined effect of these two circumstances will be to decrease the average temperature over the surface of the earth by about fifty degrees. Therefore, long before the sun reaches extreme old age, life may disappear from the earth. Yet, it has many millions of years to go before that dismal moment of cosmic evolution arrives.

Looking backward, scientists place the present age of the sun at between seven and eight trillion years. It is believed, too, that the dissipation of mass was enormously more rapid in the youthful period. In that exceedingly remote time of solar beginnings, the sun's mass was probably a hundred times greater than it is now. As old age approaches, it becomes more economical of its hoard of energy.

COSMIC RAYS

Who has not heard in these recent years of cosmic rays? Their very name indicates their source, coming as they do from every portion of interstellar space, as plentiful at midnight as at noonday and not a bit more abundant from the vicinity of the sun than from any other quarter of the heavens. First investigated by Kolhoester in Germany and Millikan in America, these once mysterious rays afford the most penetrating form of radiation of which scientists have ever had experience. The first instance of this type of electromagnetic waves came with the discovery of X-rays in 1895. Then came the gamma rays of radium, still shorter in wave length and more penetrating. Now we have the cosmic rays, vastly "harder," that is, of shorter wave length again, indicating an origin of intense activity. They ceaselessly bathe the earth and every other body in space; they pierce man through and through; they have been doing this since his first appearance upon the planet; and there are those who attribute to this phenomenon a share in shaping man's evolution. Apparently, for untold eons, probably from the very beginning of this space-time universe, this process has been in progress. If so, it leads to highly interesting conclusions, seemingly irresistible in their logic and of immense significance.

Recently, with recording electroscopes eight times as sensitive as those used in earlier experiments, Millikan and his associates have detected these rays to great depths in mountain lakes of California and with pilot balloons 0.92 of the way to the top of the atmosphere. Everywhere—at sea-level, at the bottom of high-altitude lakes or in the extreme upper layers of the earth's atmosphere—they appear to be of the same order of frequency and energy content. Millikan says his experiments "show conclusively that these rays consist of a definite and distinct region of spectral frequencies, or oscillations, a hundred times more rapid than those produced by the most powerful sub-atomic changes heretofore known, namely those accompanying radio-active processes." He has demonstrated that the cosmic rays pass through two hundred feet of water, equivalent to eighteen feet of lead. For comparison, we may note that ordinary X-rays are capable of penetrating only a half-inch of lead.

These facts point unmistakably to atomic transformations everywhere in the depths of space enormously more energetic than any with which we are familiar in our terrestrial laboratories. This conclusion is based on the fact that the rate of vibration of emitted rays and, therefore, their penetrating power are proportional to the energy released in the subatomic change which produces them. As

Millikan says, it seems certain that all through space atomic changes at least one hundred times more intense than those occurring in radioactive disintegrations are taking place. He reaches the conclusion that no disintegrating process can account for as much as a thirtieth of the energy of the most penetrating of the cosmic rays. We might be tempted to look for their origin in the heart of a star, but the powerful rays there generated, in being buffeted about on their long and devious journey to the surface, are transformed into light and heat waves. Furthermore, the uniform distribution of these cosmic rays shows that their birth-place is not confined to the stars. In fact, they are believed to originate exclusively in interstellar space.

In indicating the solution of the problem of origin, Millikan says, "If the Einstein special theory of relativity may be taken as a sound basis of reasoning—and no results predicted by it have ever thus far been shown to be incorrect, while it has many striking successes to its credit—then it follows that radiant energy can never escape from an atomic system without the disappearance of an equivalent amount of mass from that system. . . ." In his earlier investigations, he found that the energy factor of the supposed atomic changes, as indicated by the frequencies of the cosmic rays, corresponds closely with that which would result from the theoretical destruction of mass involved in the production of helium from hydrogen. We have seen in a foregoing chapter that the synthesis of an atom of helium from four hydrogen atoms will involve the disappearance of 0.032 of mass, with, of course, the liberation of a corresponding quantity of energy. Millikan now finds that the frequencies of these rays points to the building up in the depths of space of other elements than helium. He says, "Such studies reveal the fact that there are no possible transformations capable of yielding rays of the enormous penetrating power observed by Millikan and Cameron except those corresponding to the building up or creation of the abundant elements like helium, oxygen, silicon and iron out of hydrogen, or, in the case of the last two elements we mentioned, out of helium.'' In these cosmic rays, Millikan hears, as it were, the birth-cries of the infant atoms of the more common elements. For the first time in the history of science, he finds evidence of a creative process opposed to the dissipation of mass occurring in the stars. And the sequel is more interesting still.

Millikan believes it proved by spectroscopic evidence that everywhere in interstellar space electrons and protons exist in great abundance. These constitute the raw material out of which the elements giving rise to the cosmic rays are built. However, it is at once plain that, if this atom-building process is ceaselessly going on and has been doing so for countless eons in the past, any original supply of electrons and protons would long since have been exhausted. Therefore, the conclusion is irresistible that everywhere in space these atomic units are constantly coming into being in the utmost profusion. It could not be otherwise. If aggregations of electrons and protons are forever being marshaled to form atomic cohorts, the supply of subordinate material must as continuously be replenished. But what is its origin? The suggested answer to that question is truly fascinating.

Let us give this answer in Millikan's words. He says, ''The only possible answer seems to be to complete the cycle, and to assume that these building stones are continually being replenished throughout the heavens by the condensation with the aid of some as yet wholly unknown mechanism of radiant heat into positive and negative electrons.'' That is, the radiant energy of the stars, poured forth with such prodigal abundance, may afford something more than a colossal spectacle of cosmic waste. It may be that it is being turned to account in the birth of electrons and protons. At least, the logic of the situation drives one of the world's foremost physicists to that conclusion.

And what a stupendous picture this view presents! We see the radiation of the stars give rise to electrons and protons, which combine to form atoms, these in turn gathering into the primitive nebulæ, out of which stars and solar systems are born, only to transform their substance into energy once more for the repetition of the cosmic cycle. And somewhere in this vast sweep of ceaseless change may come life and man and civilizations—not once merely, but many times and in many places. On this point, Doctor Shapley in *The New York Times*, February 24, 1929, says: "Suitable physical conditions are not likely to be abundant throughout the stellar universe. To harbor organic beings, a star, which itself is hot and gaseous and impossible of sustaining life, must have planets, and it must keep them in a healthy condition during long intervals of time. We suspect a hundred million years are far too short for the development of the simplest organisms known. To arrive at a highly complicated and evenly balanced living complex, such as a beetle, a starfish, an orchid or a man, has consumed an interval of time that surpasses our ability to appreciate. Uncommon as a habitable planet may be, we are not justified in assuming an absolutely unique position for the earth in nature. The stars of our stellar system are numbered by the thousands of millions. Time is long. Sometime, somewhere, there have doubtless been many planets, besides those of the solar system, fitted for that complex of innumerable chemical reactions called protoplasmic life. The animal man, to be sure, is probably unduplicated elsewhere in the sidereal universe. Astronomically speaking, he represents such a transient, fortuitous and uncertainly poised combination of circumstances that it would be surprising if the laws of probability exactly reproduced him elsewhere. But in some form nonterrestrial life probably exists, has existed and will exist. In the absence of information, we can only surmise that the chance that it surpasses our own is as good as that it falls below our level."

And there we must let this intriguing possibility of life in other worlds than ours rest. However, in another direction, this birth of elements and the probable utilization of radiant energy in the process throws an illuminating searchlight. Elsewhere, we said something about the famous Second Law of Thermodynamics and its pessimistic message regarding the disappearance of energy levels and the eventual dissipation of the original energy content of the universe. Although we hinted at a silver lining behind the cloud of gloom, it seemed more than likely that the universe is running down. There appeared to be no reverse process whereby the energy produced in the stars should reappear in its original form of matter. As Jeans puts it: "Thus observation and theory agree in indicating that the universe is melting away into radiation. Our position is that of polar bears on an iceberg that has broken loose from the ice pack surrounding the pole and is inexorably melting away as the iceberg drifts to warmer latitudes and ultimate extinction."

Although it might be billions upon billions of years in the process of dissolution, no one likes to believe that the universe is bound to disappear, save for a vast reservoir of latent but unavailable energy. As to what this condition might be, Professor Henry Norris Russell, of Princeton, in *The Scientific American,* says: "Jeans—basing his calculations upon best available data—finds that if all the matter contained within the region of the spiral nebulæ were converted into radiation, and this radiation condemned to wander endlessly about this same region, the average intensity of the radiation would be about that of ordinary moonlight. That is, about 500 times as great as the light of the stars on a clear moonless night." This is on the assumption of a finite universe. Such an inglorious end to things as they now are would seem inharmonious in the extreme.

Happily, Millikan, the light-bearer of a new day, has come with his message of hope. If his view is correct, and there seems to be no loophole in it, the universe can not be annihilated. It is self-perpetuating. It does not matter that we can not understand how it may be possible for radiant energy to transform itself into electrons and protons. Lack of this knowledge of the mechanics of the process does not invalidate the theory. This is not the first time that scientists have been in a similar predicament. The bare mention of the ether, electromagnetic waves, the present status of the atom and the quantum theory will afford abundant illustration. Yet, many are not so optimistic as Millikan. Professor Russell says: "It may be that atoms are reformed from radiation somewhere in space, but we have not the least evidence they *can* be so formed—much less that they are. Our speculative thought has wandered far beyond the bounds of experience and the knowledge based on it, and the only sound intellectual position on this question is agnostic. We simply do not know." Still, what is obscure to-day may be flooded with sunlight to-morrow. That has been the experience of the past. It will be so again.

Nothing more alluring than the cosmic cycle here outlined has been suggested by the researches of science in a century. Few there are who could wish for the eternal twilight of all created things.

CHAPTER X

Physical Discovery and Civilization

SCIENTIFIC DISCOVERY THE BASIS OF CIVILIZATION—LIGHT'S GOLDEN JUBILEE—LANGMUIR'S INVENTION OF THE GAS-FILLED BULB—RELATION OF PHYSICS TO PRODUCTION OF POWER—WATT AND THE INDUSTRIAL REVOLUTION—CARNOT'S CONTRIBUTION—INTERNAL-COMBUSTION ENGINE — ELECTRIC AGE — CULTURAL ASPECTS OF SITUATION—TRANSPORTATION—FROM SAILS TO STEAM—EPIC OF STEAM LOCOMOTION—ELECTRIC TRACTION—DEBT TO PHYSICAL RESEARCH—METEORIC RISE OF MOTOR-CAR—THE AIRPLANE—COMMUNICATION—TELEGRAPH, TELEPHONE AND RADIO—PHONOGRAPH—ENGINEERING TRIUMPHS—PRACTICAL RESULTS FLOWING FROM DISCOVERIES IN PHYSICAL RESEARCH—A UNIQUE MUSEUM—OTHER ASPECTS THAN THOSE OF MATERIAL PROSPERITY—A DEFINITION.

The story of physics has forever kept in step with the marching song of civilization. To one who has read the foregoing chapters it is hardly necessary to emphasize this connection. From a mastery of the physical laws of Nature has flowed that economic surplus and leisure without which education, invention, science, art, literature, democratic government, enlightened statesmanship and organized religion would disappear and civilization be swallowed up in the abyss of barbarism. Even the caveman worked in harmony with the laws of the physical world. The world was cruel to him only to the extent that he did not understand and know how to use the great natural forces with which he was surrounded. Gradually, as he made discovery after discovery, he mastered his environment, and the resulting material prosperity provided a modicum of time for the development of a rude culture. Gathering momentum with the centuries, this growing fund of physical knowledge has become the most potent factor in world progress. Does this sound materialistic? It is no more so than the facts warrant. Even in religion, without the discoveries of science, superstition would rule more largely than it does to-day. Who can gage the influence upon human thought, religious and otherwise, of the Copernican view of the heavens, corroborated by the discoveries of Galileo and established by the achievements of Newton? In our own time, the Einstein theory is displaying a dominance almost equally potent. Under its sway, minds broaden. Men grow in mental stature. The earth-bound conceptions of reality fade, horizons recede. We become citizens of the universe, and this is civilization.

There are so many available illustrations of this fundamental relationship between human progress and the growth of physical knowledge that one is lost in a forest of possibilities. It matters little where we begin. Suppose we take a comparatively recent example.

Recently we observed in this country "The Golden Jubilee of Light." The other day at Chautauqua, New York, I saw the man whose invention we celebrated and heard him speak. Before me as I write stands a reproduction of that first incandescent lamp. As I look at this prophetic token of a new day in world lighting, I try to picture what the last half-century of progress would have been without it and its successors. We should never have known the sunlike radiance of home and office, factory and workshop; brilliantly lighted thoroughfares and "Great White Ways" would be but iridescent dreams of the future; theater and moving-picture house would still be dependent upon the now obsolete calcium light of a generation ago; the illumination of a world's fair or an ocean liner would be tame in comparison with the present reality; country homes would even yet be condemned largely to the use of the tallow candle and kerosene lamp; while the infinite satisfaction arising from being able to press a button and thus chase away the darkness would never have been experienced. The wonderful lighting displays which characterized the observances of this anniversary were but a slight emblem of what this invention has meant in the lives of millions of people. And back of it all stands the harnessing of natural forces, the practical application of physical laws. It affords a remarkable example of the relation of physical discovery to civilization.

In the subsequent research in this same field, we find another notable illustration. Dr. Irving E. Langmuir, one of America's foremost physicists, tells us that two decades ago he went from his post as an instructor in Stevens Institute up to the laboratories of the General Electric Company, at Schenectady, New York, to spend his summer vacation. Dr. Willis R. Whitney, director of the laboratories, told Langmuir that he might browse about for several days until he found something which interested him. It so happened that the whole laboratory force was at that time working on the problem of drawn tungsten wire, the wire now universally used as the filament in incandescent lamps. Three samples out of a large number had been found which worked as well on alternating current as on direct, but no one knew why. The immediate problem was to discover the reason. Langmuir says: "It seemed to me that there was one factor that had not been considered—that is, that the offsetting might possibly be due to impurities in the wire in the form of gases. I therefore suggested to Doctor Whitney that I would like to heat various samples of wire in high vacuum and measure the quantities of gas obtained in each case." And so he went to work on a trail which might lead somewhere or nowhere.

In a short time, Langmuir had discovered that these filaments gave off astonishingly large volumes of gas, sometimes as much as seven thousand times the volume of the filament itself. In speaking of this circumstance, he says: "I spent most of the summer trying to find where this gas came from, and never did investigate the different samples of wire to see how much gas they contained. How much more logical it would have been if I had dropped the work as soon as I found that I would not be able to get useful information on the 'offsetting' problem by the method that I had employed." However, he did not, for which the world may well be grateful. Continuing, he says: "That summer's work was so interesting that I dreaded to return to the comparative monotony of teaching, and gladly accepted Doctor Whitney's offer to continue at work in the laboratory. No definite program of work was laid down. I was given first one assistant and then others to continue experiments on the sources of gas within vacuum apparatus, and a study of the effects produced by the introduction of various gases into tungsten filament lamps. The truth is that I was merely curious about the mysterious phenomena that occur in these lamps. Doctor Whitney had previously found that gases have a habit of disappearing in lamps, and no one knew where they went to, so I wanted to introduce each different kind of gas that I could lay my hands on into a lamp with a tungsten filament and find out definitely what happened to that gas."

Langmuir tells us that this work proved to be most fascinating. Still, it did not seem to be leading toward any practical results, anything that could be translated into dollars and cents on the balance sheet. Apparently, he was merely gratifying that scientific curiosity mentioned above, hardly realizing probably that a scientist's curiosity is frequently scientific dynamite of the most powerful sort. Time and again, Langmuir went to Whitney, telling him that this investigation did not seem to be leading anywhere in particular. But Whitney, in the true spirit of research, answered that this did not matter so long as it added to the knowledge of what takes place in an incandescent lamp. And so Langmuir worked on for three years, finally giving to the world the gas-filled bulb, which, together with the tungsten filament, saves the American public a billion and a half dollars a year on its lighting bill. And as every one knows, this discovery has increased notably the quality of electric illumination.

No small benefits are these to be credited to the acquisition of an additional fragment of physical knowledge. Factors, they are, in the progress of civilization. And back of it all and making it possible stands a multitude of discoveries in the field of electricity. At every point, this progress was the outgrowth of applied physics, following the discovery of fundamental principles.

THE GROWTH OF POWER

Probably nowhere else is this relation of physics to the progress which we call civilization better illustrated than in the development of material power. In the early centuries, man-power was the only power available for carrying the world's burdens and performing its tasks. Frequently, bought with the sweat and grime of the bondsman, it became the symbol of human drudgery. The pyramids are monuments to this phase of man's progress. Even until quite recent times, human brawn was the biggest factor in tilling the soil, mining and smelting ores, erecting buildings and transporting goods. For centuries, the ox and the horse had been put to use, but still man had not learned to turn to his account the natural forces with which he was surrounded in lavish abundance. At length, he harnessed the waterfall and the racing wind, thus lifting from the backs of men a little of their former burden. The mill became the symbol of a coming age, and the use of machinery grew apace. But water-power was available only here and there, and there was no means of transporting it to distant places. A new conquest of physical laws was needed, and in time it came.

The story of how Watt put the speeding molecules to work is old. His discovery had been forecast by a long line of inventive predecessors, from Hero of Alexandria in 200 B. C. to Thomas Newcomen of Watt's own century. As clearly as the mastery of fire marked a decisive turning-point in the early progress of men, Watt's introduction of steam into the workshops of the world inaugurated the first industrial revolution. For it was Watt who gave us the practical steam-engine of the modern era. What that invention meant in speeding up material progress, in unlocking the resources of the earth, in developing power-driven machinery, in improving the lot of workers and in making this planet a more pleasurable place in which to dwell—few can appreciate to-day.

Watt had worked with Joseph Black at the University of Glasgow and knew something of the latter's theory of latent heat. The task of repairing a model of the Newcomen engine in his capacity of instrument maker at the university afforded the stimulus for the investigation which resulted in his epoch-making invention. He saw the appalling waste of energy involved in cooling the cylinder after each stroke, as was required in the operation of the Newcomen engine. Watt determined to eliminate this fundamental defect. The result was the double-acting steam-engine, which with improvements has remained standard to the present era. A generation later, Sadi Carnot, of France, worked out the fundamental principles underlying the operation of the steam-engine, thereby reducing the theory of it to a science. Thus, emerging from unnumbered centuries of toil and in response to human necessity, mechanical ingenuity and theoretical science there was born an invention which ushered in an unparalleled epoch in material prosperity.

Without the steam-engine, the material civilization of the world would stand to-day where it did at the time of the American Revolution. Hand and water-driven machinery would still prevail in factory and shop. The day of small things would yet be with us. Standards of living would have gone backward, not forward, for the eighteenth-century basis of industry would have been inadequate to meet the needs of constantly increasing populations. Indeed, the dire calamity predicted by Malthus has been averted only by the application of scientific principles to industrial production, and chief among these has been the power derived from the expansive force of steam. And steam is still paramount. Despite the wide-spread development of water-power, the bulk of the world's electricity is generated by steam produced from coal. But coal, which will continue to be the basic source of power for many centuries to come, had been available from man's earliest appearance upon this earth millennia ago. Nevertheless, its use for power purposes had to wait the coming of the physicist.

The development, too, of the internal-combustion engine was a matter of physical research. In the last generation, the gasoline and Diesel motors have solved the small power problems, as the steam-engine did the big ones. We have only to mention the automobile, the airplane and the Diesel-driven yacht to make this point clear.

And what of this electric age with its vast power plants, its long-distance transmission lines, making possible the utilization of power at points far from the source of energy, motor-driven machinery everywhere and multitudes of electrically equipped homes? Does this not all go back to the researches of Faraday and his predecessors? You step into an elevator and are quickly borne to the upper floor of an office building in a big city, entirely oblivious to the fact that the power used may have been generated at a mountain waterfall several hundred miles away. It is practically feasible to-day to run subway trains in New York City by electric power from Niagara Falls. In scores of rural sections of our country, lines for light and power pass by the farmer's door. Is this what we mean by civilization? If so, it is but the realization of a physicist's dream. Illustrations of electric power in meeting human needs might be multiplied indefinitely. And the possibility of it all goes back to that long line of electrical investigators stretching from Sir William Gilbert and Otto von Guericke to Westinghouse and Edison.

And we must not forget the steam-turbine, one of the most beautiful adaptations of the energy of moving molecules to mechanical purposes that ever traveled the highway from an inventor's brain to material expression. Free from vibration, encompassing a vast amount of power in small space, light and efficient, these modern engines are widely used to drive ocean liners and for the generation of electric power.

Every type of power motor, from the big turbines of the *Majestic* to the half horse-power unit of the workshop and home, operates in accordance with the fundamental principles of mechanics and the laws of motion. Each requires in its design the skill and the knowledge of physical laws of an expert engineer. Its adaptation to the use of the energy of heat or electricity is the result of a mastery of technique acquired through two centuries of apprenticeship to the physical habits of Mother Nature. And this is physical discovery in its practical aspects.

Does this solution of the power problem present no cultural aspects as well? Who would like to revert to the industrial conditions prevailing a century and a half ago? Does any one seriously contend that education would be more generally diffused, that social conditions would be better, that morals would be on a higher plane, that men's minds would be broader, that philanthropy would be more in evidence, that art and literature would be more flourishing—in short, that what we choose to call culture would be further advanced than now? Is there no relation between the material and the esthetic? Are not the comforts and the luxuries which to-day have superseded the necessities of yesterday a contributing factor of vast import in the development of the higher life? Do not these multiplied contacts resulting from applied science, these larger experiences in living, also enrich the soul as well as the physical being and promote the growth of a cultural civilization? Despite the jazz of the present age, are there not notable conquests of the opposite sort at innumerable points of the advancing front? We can not see ourselves in perspective.

History will take care of that. But who fears the verdict of history?

TRANSPORTATION

It is but a step from the subject of power to that of transportation. The two go hand in hand. The motive power of industry has always been identical with that of moving vehicles and ships upon the sea, save in the "unchanging East," where the faithful camel and the elephant have been from time immemorial chiefly burden-bearers of transportation. In Europe, until the coming of steam, canals were the only innovation in the means of transport. Canals are old. In the third millennium before Christ, the Babylonians employed them for transportation, irrigation and defense. Engineering works they were, bristling with the application of physical laws. In the second millennium, the Egyptians built a canal connecting the Red Sea with the Nile, thereby anticipating the Suez Canal by more than thirty centuries. In the Middle Ages and after, these waterways appeared in Europe and in England. Upon the seas, the galley ships of the ancients gave way to sailing vessels, putting to use in a score of ways the slowly accumulating fund of physical knowledge, but for centuries nothing better appeared in sight.

Then came steam, inaugurating a revolution in transportation, as it had done in industry before it. Steam locomotion has but recently turned its first century of progress. And what a century it has been! Had applied science deliberately sought to build for itself a monument of achievement, it could not have succeeded better than it has done in this field. As I contemplate the Atlantic ferry, I see in imagination the little craft of the Vikings making their way through the cold northern waters, strewn with icebergs; then there passes in review the tiny ships of Columbus, the larger sailing vessels of a later day, the *Savannah*, in 1819, a cross between a steamship and a sailing vessel, to be followed by the *Sirius* and the *Great Western*, the first real steamships; in 1840, came the first Cunarder, reducing the crossing time of the Yankee Clippers from sixteen to thirteen days and being succeeded by faster and faster vessels of a similar type until the coming of the "ocean greyhounds" in the 'seventies with a record of little more than six days; with the turn of the century, steam navigation cut the time to a little less than five and a half days, and recently the *Bremen* crossed from Cherbourg Breakwater to Sandy Hook in four days, seventeen hours and forty-two minutes, thereby clipping nine hours from the *Mauretania's* record.

And on inland seas and rivers, steam has made conquests no less impressive. What does the development of our great Middle West not owe to the steam navigation of the Mississippi and the Ohio and their tributaries? Without the navigation of the Great Lakes, access to the world's richest mines of iron ore, beyond Duluth on Lake Superior, would be seriously handicapped. To-day, the project for a lakes-to-the-ocean steamship route engages the thought of the best statesmanship of Canada and the United States. In Continental Europe, the picture does not vary. And let us not lose sight of the circumstance that these benefits are the product of a knowledge of physical forces and how to apply them. If they have any bearing upon the progress of civilization, we must credit it to physical discovery.

The epic of steam locomotion on land is a romance to which we can not do justice here. From Stephenson's *Rocket* to the *John B. Jervis* of the Delaware and Hudson with its four hundred pounds of steam pressure to the square inch stretches a long pathway of continuous progress in physical discovery and its application. Upon it has hinged the development of continents, the feeding of nations, the migrations of peoples, the growth of democratic government, the free intercourse of distant parts of empire, the dissemination of ideas and the spread of learning. For a century, the whistle of the locomotive everywhere has been a symbol of progress. In our own country, fading in the distance before this forward march of a new civilization, we see the red men, the herds of buffalo, the pony express, the Indian fighters of the ever-vanishing frontier, the covered wagon and the rugged pioneers of vast spaces.

But the supremacy of steam, picturesque and splendid as has been its record of conquest, is threatened. Electric locomotion is rapidly encroaching upon its once proud domain and extending its boundaries. Let us have a picture of what this revolution means, taken from an article by the author in *St. Nicholas Magazine.*

> "Come with me to Harlowten, Montana. Before us stretch the Big Belt, the main range of the Rockies, the Bitter Root Mountains and the Cascade Ranges beyond, some of the most rugged and majestic scenery to be found on the American Continent. We take passage on a train of a thousand tons. Noiselessly, without jar or vibration, almost imperceptibly, the train gets under motion. Drawn by some invisible power, this monarch of the mountain highway, swiftly and smoothly, moves forward through an ever-changing panorama of magnificent scenes. Now it threads the crags and then again holds fast to the cañon walls. No sense of insecurity is felt. We seem to be in the hands of a mighty giant in whose sure keeping no harm can come to us. The mountain-sides, touched by the sunlight, seem to be kindled with the glory of a thousand shades and hues. But no clouds of smoke from panting engines intervene to obscure the view. We enter a tunnel, and to our surprise no suffocating gases or cinders fill the car. It is winter, but the genial warmth of electric heaters chases away the cold. There are no frozen steampipes, no bothersome stops for coal and water, no straining from laboring engines. The flow of a seemingly inexhaustible motive power is smooth and even. One seems to glide over the rails with an unexpected degree of speed and comfort."

Edison, after he had traveled this route, gave the following impression of his experience: "No grinding, no jerking, no puffing, no straining, no disturbed slumbers—just a keen sense of moving swiftly, of being propelled by power vastly in excess of requirements. You ride with ease—you are at ease—it is the very last word in transportation."

In our great suburban areas, electric traction is solving the problems of commuter and traffic manager alike. Everywhere railroads are electrifying their terminals. In the newly constructed Union Terminal in Cleveland, a single electric locomotive handles with ease and dispatch seventeen seventy-five-ton Pullman cars.

And the electric locomotive is more powerful. On the Mexican Railway between Mexico City and Vera Cruz, ten such giants of the modern era are doing the work formerly performed by twenty-three steam locomotives. And this experience is typical. Every country in Europe is following the lead set by America. To-morrow, this new motive power of the twentieth century will dominate the highways of travel and commerce.

Do we need to remind any one that this progress is the direct outgrowth of the researches of Faraday and his successors in the field of induced currents? In the days of Galvani, Volta and Franklin, such achievements were not as much as visions in the imagination of the boldest dreamer. Not even Faraday or any of his successors for a generation had the faintest glimpse of the present picture. Indeed, progress is sometimes so rapid that it startles those who are now participating in it. And this is what the discoveries of physics are doing in one small corner of the industrial world to perpetuate the civilization of what will some day be another antiquity.

Let us not forget, too, that putting the molecules to work in the form of compressed air has made possible the marvelous braking systems and their control of our ever-lengthening trains. Compressed air also enables a single guard on a long subway train to operate the doors of all the cars. And consider our elaborate signaling systems for the safety of passengers and traffic. In the centuries of research between the caveman and the present, chiefly since the time of Newton, the foundations for these strategic pivots of modern progress were laid down in terms of original discovery.

Without such discovery, civilization as we know it would never have appeared.

When we come to the meteoric rise of the motor-car, we are dealing with a phase of transportation whose very inception lies well within the memories of many of us and with a chapter of the story which has only just begun. What the Great War would have been without motor transport, it is difficult now to picture. Were we to blot out of existence to-night every motor-car of every description, where would industry, commerce, social intercourse and recreation begin to-morrow? What would become of agriculture without its tractors, its trucks and motor-driven harvesting machinery? And what of the rapidly rising tide of motor-carried passenger traffic? How would school children get to our centralized institutions of learning? Should we impress the horse once more to deliver merchandise, carry us from place to place and become the slave of farm and factory? Who would like to see him, faithful beast though he was, again reign supreme on city street and country highway? For this mechanization of traffic, we have to thank the physicist. And what a bundle of mechanical principles and physical discoveries we find embodied in every motor-car! Motor, transmission, gear-shift, brakes, lights, lubrication, horn and much more paint for us a picture of the concentrated thought, the flashes of genius, the unremitting toil, the mistakes retrieved and the failures turned to victory which have translated dreams into the legal tender of successful achievement.

Still, this is not all. Can you find anywhere in the history of physics a more typical illustration of the mastery of Nature's ways than that of the airplane? A short generation ago, a distinguished American scientist announced that flight with a heavier-than-air machine would be impossible without the discovery of some theretofore unknown physical law or some new light metal. His prophecy had hardly been uttered before the Wrights were flying at Kitty Hawk. The "impossible" in the physical world has happened so many times in recent years that it scarcely behooves any one to say that anything can not be done. Before it gets into print, it is usually out of date. Yesterday the airplane was a dream; to-day it is a marvelous reality; to-morrow it will be a commonplace necessity of transportation. And all because venturesome spirits dared to believe that science might command the air.

COMMUNICATION

The communication of ideas, sending messages, filling the "ether" with music and speech—these are some of the flowers that blossom on the tree of scientific research. A hundred years ago, the fastest means of sending intelligence from point to point was by means of courier or by flashing beacon lights from hill to hill. The telegraph had not yet come. The electromagnet was a plaything of the science laboratory. Faraday had not discovered the principle of induced currents. Even after the telegraph had sent and received those immortal words, "What hath God wrought?" it was a generation before the telephone was carrying the spoken word. Then came Hertz with his electromagnetic waves, and Marconi and De Forest and a host of others, bringing in the wake of their discoveries the radio age.

I sometimes allow my thought to wander to the bleak windswept coast at St. Johns, Newfoundland. It is December 12, 1901. In an upper room of an old barracks sits Marconi and two assistants. Three hundred feet below, the surf breaks in a mighty roar and outside the wind is blowing a gale. In the teeth of it all, a kite aerial has been raised four hundred feet and holds. Marconi presses a receiver to his ear. The little room is tense with suppressed excitement. Will the signal fail them? The moments seem hours. The prearranged time has arrived, and nothing happens. Then, it comes. Yes, there are the three dots of the letter "S." The decoherer clicks. Marconi hands the receiver to his friend. There can be no mistake. Transatlantic wireless has passed into history.

To-day, New York talks in reciprocal telephone conversation with London and the Continent. Talking movies and television are here. Yes, television in natural colors. The broadcasting of motion pictures for the home is not far away. What to-morrow will not bring, the boldest skeptic dares not declare. Applied physics is on wings, and let no one fancy that it has reached the end of its flight. Already, a presidential campaign has been fought out over the radio —a perfectly unbelievable development less than a decade ago. A new factor has come into politics. Democracy is moving forward, and it is keeping step with the music of scientific discovery.

A present crowning achievement in communication was recorded the other day. Of it, *The New York Times* said, "The deep bass notes of Westminster Abbey's mighty organ encircled the earth for the first time a week ago this morning (July 7, 1929), in thanksgiving for the recovery of King George V. The music and the words of 'God Save the King' traveled on the wings of radio to reach all parts of the British Empire over which waves the Union Jack, upon which it is said the sun never sets. It was a remarkable test for radio broadcasting, and in it a glimpse of the future can be caught, when Presidents and Kings will speak to the population of the earth as easily as though conversing with a friend in the same room. It leads to predictions that inaugurations and coronations will be heard 'round the earth."

Who has not marveled at the thought that he can place upon his phonograph a record made by Caruso and listen to the voice of the dead artist? What would we not give if we might hear the great musical compositions executed by the masters? Thanks to the knowledge provided by the physicist and the technique of the inventor, this wished-for privilege will in succeeding generations become a reality.

Every day this earth grows smaller. Isolation becomes a relic of the Dark Ages. Is this a factor in the forward march of civilization? If so, we must credit its presence to scientific discovery.

SUCCESSORS OF THE PYRAMID BUILDERS

On August 14, 1914, just at the beginning of the Great War, President Wilson by official proclamation opened the Panama Canal to the traffic of the seven seas. The next day, the *Christobal* made the trip from Atlantic to Pacific in nine hours and forty minutes. The monotony of the time-consuming journey around the Horn had become but a memory, an emblem of a former age. The pressure of a few electric switches had tapped reservoirs of power, which smoothly, silently, lifted the great ship as gently as a babe over an eighty-five-foot hill and let it down into the waters discovered by Balboa, forty-two miles from the port of entry at the eastern terminus. In seven years, a year less than the specified time, modern engineers, the successors of the pyramid builders and of other creators of the mighty works of antiquity, had cut a channel connecting two oceans and establishing a coveted trade route for world commerce.

This monument to American enterprise, now the most heavily burdened ship canal of the world, is typical of what applied physics is doing in the field of engineering. For engineering is physics in one of its most practical aspects. Let us glance at what happened in one corner of that gigantic undertaking. During the construction, in the Culebra Cut alone, 167 locomotives puffed away; 1250 flat-cars shuttled to and fro over 112 miles of track laid on the face of the cliffs, winding snake-fashion across and back; every two minutes the heat requirements of shovels and engines necessitated the burning of a ton of coal; each minute, steam-shovels lifted from their ages-old resting-place a dozen car-loads of rock and earth; every hour a ton of dynamite was exploded; the workshops fairly bristled with compressed-air and electric-driven machinery, forging presses, foundries, traveling cranes and much more—all of which is a tribute to the physicist's mastery of Nature's ways. Had there been no discoveries of natural laws, these big-scale methods would have been unknown.

Similar methods have but recently thrust a vehicular tunnel beneath the Hudson, connecting two states; they have, in the Moffat Tunnel, conquered the Continental Divide, thus opening the vast natural resources of northwestern Colorado to eastern industry and commerce; from Scenic to Berne in the state of Washington, they have pierced the Cascade Range, thereby boring the longest tunnel in America and overcoming one of the most formidable obstacles to transcontinental traffic; every subway built beneath the skyscrapers of New York or driven under its bounding rivers is a monument to the genius of the engineer and his familiarity with physical laws. Everywhere, these modern successors of the pyramid builders are applying the knowledge accumulated by the scientists. How much easier might have been the more than herculean task of those human machines by the ancient Nile, had they, too, possessed this knowledge!

And so one might continue. This old earth abounds in these works of the engineer. They are a bit of concrete evidence of the ever-growing contribution of applied science to the progress of civilization. True, civilization would have advanced without these strides in scientific attainment, but the process would have been infinitely slower, and the quality of the product would have been different. Would it have been better? Who knows?

FROM OTHER ANGLES

Some one asked Professor Michelson why he spent so much time in measuring the velocity of light, and he replied, "Because it is such good fun." Probably no keener joy is ever experienced than that which accompanies original discovery. And every one participates in the advances flowing from such discovery. There is no particle of truth added to the sum total of human knowledge which does not find its niche of usefulness. Scores of blind alleys have led to broad highways of material progress. The discoveries in pure science of to-day become the tools of the workshop and the laboratory to-morrow.

Who would have thought that the discovery of helium in the atmosphere of the sun would become a factor in the safety of airships? What relation could there be between the invisible radiations of Röntgen's vacuum tube and a method for determining the quality of structural steel? Would anybody have dreamed that the Polish girl's quest for radioactive elements might lead to a method for treating cancer? What more fanciful than to imagine that Maxwell's equations should inspire a search which was to end in the radio conquest of space? Did Davy, as he performed those experiments in chemical decomposition at the Royal Institution, have the faintest glimpse of the vast electrochemical industry of which they were the forerunners? Absurdly accidental, is it not, that Galvani's experiments with the frog's legs should lead to the first method of producing current electricity?

The history of physical discovery is full of examples such as the foregoing. Its development has grown out of them. And with them has come improvement in the lot of men. Without these discoveries and their sequels, we should stand where the cavemen stood. Our homes would be the miserable hovels of primitive men; the medicine-man would still rule in the battle with disease; science, art, literature, statesmanship and enlightened religion would as yet be unborn and barbarism would stalk in our midst.

In Chicago, there is in the course of preparation the most unique museum in America and one of the most remarkable museums in the world. In the old Fine Arts Building of the World's Columbian Exposition of 1893, rehabilitated for the purpose, is being assembled the most complete portrayal of the scientific and industrial advances of civilization that has ever been seen. It proposes to picture in hundreds of exhibits, covering acres of floor space, man's industrial, economic and social progress from the era of the caveman to the present moment. Each epoch will live again. There, silhouetted against the background of the ages, one will see, step by step, man's progress. No phase of his activity will be omitted. As one walks through the miles of avenues and tarries on the way, he may easily imagine himself back amid the scenes and various stages of culture of other centuries. Never before has it been possible to trace the influence of scientific discoveries upon every aspect of man's progress as it will be in this museum. And it is a most illuminating story that those exhibits will tell. One will literally see the foundation stones of science. The boasted achievements of the present age will stand forth in their true perspective. Their relationship to a multitude of earlier advances will be inescapable. Most striking of all, however, will be the overshadowing significance in the evolution of civilization of scientific research. In particular, physical discovery will blaze with the steady radiance of a star of the first magnitude.

Yet, big as is the contribution of physical discovery to material prosperity, there are large areas of its domain far removed from such considerations. How can the discovery, for instance, that our solar system is fifty thousand light years from the center of our galaxy of stars ever pay any dividends? No industries, whose shares will be quoted on the stock exchange, can be founded upon it. And what bearing can Einstein's conception of curved space have upon the temporal and spatial activities of mortals on this planet? Suppose we could discover that petroleum exists in prodigious quantities in the crust of the moon. That would in no way influence the price of gasoline at the curb. Yet, the circumstance would be head-lined everywhere, and people in every walk of life would be profoundly stirred. The possibility of life on Mars, though utterly beyond contact with ours, has evoked the deepest interest. The message of Millikan's cosmic rays has required translation for the multitude. The interest in Einstein has been impressive. Whether light consists of waves or particles is of more than academic moment. The phenomena of Nature are universal in their appeal. And it is to the glory of physical discovery that the practical products of its research are incidental, and never the main objective.

The whole story is summarized in the definition of education given by Newton D. Baker: "Education is the cultivation of and the prolongation of the curiosity of childhood." So long as the race retains this curiosity, science will be secure and civilization will not decay.

THE END

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REFERENCE BOOKS

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3 [illegible] String of [illegible]
(Stone; magnets

Electricity

3 Sir J. Frazer
Gilbert's experiment; sphere of lode-stone and suspended needle.
4 " : "[illegible] things are vile".
1 Carthusian monks jumped in unison
1 Electromagnetism: "Such accidents only meet those who deserve them": Lagrange
7 (Good examples of [illegible] on powder
[illegible] ; magnetic molecules
54 Edison's [illegible]
9 Faraday's noble choice / even [illegible] himself
4 Maxwell in [illegible]
[illegible], Enc. Brit. 9th ed.

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of [illegible]
"— disadvantage of [illegible]"

density: mass per unit volume
work: force · distance
Power: rate of doing work

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